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PLATE 1.
1.—Stem of *L. pilosus* (X approx. 1.3).
2.—Stem of *L. digitatus* (X approx. 1.3).

6.—The Naturalised and Cultivated Species of Lupinus (Leguminosae) Recorded for Western Australia

By J. S. Gladstones*

Manuscript received—13th February, 1957

The identity of cultivated and naturalised species of *Lupinus* in Western Australia is discussed, and a key is provided for the identification of the 9 species considered. Since no original type specimens have been available for consultation, all remarks and conclusions are based on local material and published descriptions.

The "West Australian blue lupin," previously known in Australia either as *L. varius* L. or as *L. pilosus* L., is identified as *L. digitatus* Forsk. Its somatic chromosome number is 32.

Introduction

At least 9 species of lupins (*Lupinus* spp.) are known in Australia, either cultivated or as naturalised aliens. Of these, four or five could be classified as "agricultural," and are in the main confined to the agricultural areas of South-West Western Australia. The remaining species constitute the ornamental lupin varieties which are grown in the temperate parts of Australia. There are no indigenous lupins.

The nomenclature of these species has been a source of considerable confusion, probably arising from a lack of adequate available literature. Such keys as have been readily available have been mainly regional, and have not only been inadequate but in some cases contradictory. In the present paper an attempt is made to clear up this confusion in so far as it concerns the species occurring in Western Australia. Only those species known to be present are dealt with, although reference is made to others.

Identity of the "West Australian Blue Lupin"

Opinion in Australia has long differed on the diagnosis of this species. It was originally known as *L. pilosus* L. (Gardner and Elliot 1929), but this appears to have later changed to *L. varius* L., for it is by the latter name that the species has been known in more recent West Australian publications, e.g. Gardner and Bennetts (1956). However, Black (1948) calls it *L. pilosus*, and in the C.S.I.R.O. publication "Standardised Plant Names" (1953) preference is given to this name also.

A study of the literature has revealed some disagreement among European botanists. Nevertheless, it is plain that *L. varius* differs from the West Australian blue lupin in several important characters. Three of the most clear-cut are as follows:

(1) *L. varius:* lower flowers of raceme tend to be alternate, upper flowers verticillate; W.A. Blue: all flowers verticillate.

(2) *L. varius:* upper lip of calyx 2-toothed only; W.A. blue: upper lip deeply 2-partite.

(3) *L. varius:* upper surface of leaflets glabrous or glabrescent, lower surface hairy; W.A. Blue: both surfaces hairy.

These three points appear consistently in the descriptions of *L. varius* seen (those of de Candolle 1825, Hegi 1923, Chevalier and Trochain 1937), and allow the conclusion to be reached with reasonable certainty that the West Australian blue lupin is not the same species as *L. varius*. It corresponds rather to the species described in 1828 by Gussone as *L. cosentini* Guss., not only as regards the three characters listed above, but also as regards a number of others. There is little doubt that the two are identical. Gussone's description is, however, antedated by that of Forskal (1775), who named it *L. digitatus* Forsk. Unfortunately, the latter description is not a very full one, and it is inaccurate in describing the species as a perennial, as pointed out by Boissier (1872). Nevertheless, the synonymy of the two appears to be agreed upon (Boissier 1872, Fiori 1925, Zhukovsky 1929), although there has been no general accord on the matter of priority, and both names appear in the literature with similar frequency. If it can be assumed that they are in fact synonyms, however, *L. digitatus* must take priority since it is the earlier, and it follows that from the evidence available the West Australian blue lupin should be known as *L. digitatus* Forsk.

Malheiros (1942) found a somatic chromosome number of 32 for *L. digitatus* (as *L. cosentini*), which is the only record in the literature of this number in a *Lupinus* species. Counts by the present author have shown that the somatic chromosome number of the West Australian blue lupin (Accession N. 2086) is likewise 32, which provides additional evidence in favour of the above identification, although it cannot be regarded as conclusive since not all the chromosome numbers within the genus are known.

The very similar species *L. pilosus* Murr. can be shown to differ from *L. digitatus* in several characteristics, although there has been no general agreement that the two are distinct species. It should be noted that the author of *L. pilosus* is J. A. Murray, who edited the 13th edition of Linnaeus' "Systema Vegetabilium" (1774). Authority is often attributed to Linnaeus.

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Coste (1901) described *L. pilosus* and *L. cosentini* as being synonymous. More recently Chevalier and Trochain (1937) are emphatic on this point. On the other hand, Agardh (1835) and Boissier (1872) make a specific distinction between the two. Some writers are of the opinion that *L. digitatus* (or *L. cosentini*) should be classified as a sub-species of *L. pilosus*. Thus Fiori (1925) calls it *L. pilosus* Murr. Ssp. *cosentini* (Guss.), but Zhukovsky (1929) renames it *L. pilosus* L. Spp. *digitatus* (Forsk.) Zhuk., the *digitatus* replacing *cosentini* for priority reasons.

It can readily be demonstrated, however, that *L. pilosus* and *L. digitatus* are distinct species, on the following grounds:

(i) The two can be consistently distinguished on traditional taxonomic characteristics.

(ii) Numerous attempts by the author at artificial crossing between the two have been unsuccessful. In the *L. digitatus* × *L. pilosus* cross, pods were formed which in every case contained only empty and shrivelled seed coats, whereas artificial self-pollination of these species regularly produces good seed. In the *L. pilosus* × *L. digitatus* cross there was no sign even of pod formation.

(iii) The chromosome numbers are different. For *L. pilosus* two counts are recorded in the literature. Savcenko (1935) found a somatic chromosome number of 40, and Tuschnjakowa (1935), 42. The writer has confirmed the latter number of 42 (for accession N. 1999), and has found, as mentioned above, 32 somatic chromosomes in *L. digitatus*.

Apart from *L. pilosus*, at least two other species appear to be similar to *L. digitatus*. *L. palaestinus* Boiss. (1849) differs in that the flowers are yellow tinged with blue and the pedicels scarcely shorter than the calyx, as against blue flowers with pedicel only about one-third the length of the calyx. The recently described species *L. tassilicus* Maire (1933), which is native to parts of the Western Sahara and Senegal, has alternate or sub-alternate flowers, as against verticillate flowers, but otherwise appears to be very similar (Chevalier and Trochain 1937).

Identity of Other Species

The true *L. pilosus* Murr. is sometimes found in Western Australia but has generally been reported as *L. hirsutus* L. (e.g. Thomas and Shier 1925). The misidentification comes about presumably on account of its hairiness. Some confusion may also have been occasioned by the fact that the flowers were originally described by Murray as being pink. In the wild state the species is usually, perhaps always, blue flowered. In cultivation, however, other colours are common, particularly pink, so it is quite probable that it was from one of these cultivated varieties that the original description was made.

A species for which alternative names are used in Australia is *L. albus* L., which is often known as *L. termis* Forsk. The differences by which the two were separated in some of the older keys, namely the presence or absence of bracteoles and the degree of blue tinting of the corolla, are now regarded as being no more than varietal differences, and the two are normally brought together under the earlier designation of *L. albus*.

Descriptions of Lupinus Spp. in Western Australia*

(i)—**L. mutabilis** Sweet, Brit. Flow, Gard. 2 t. 130 (1825)

L. cruckshanksii Hook. in Bot. Mag. 58 t. 3056 (1831)

L. mutabilis Lindl. in Bot. Reg. 18 t. 1539 (1832)

The largest of the annual ornamental species, reaching 0.5-1.5 m, moderately branching, with stout hollow stem, becoming woody; glabrous or almost so except for pods. Leaflets 7-11, oblong-obovate. Raceme 10-30 cm in length, with a fairly long peduncle (6-17 cm). Flowers large and showy, verticillate in distant whorls, with long pedicels, falling rather readily; blue, white, pink or purple, with centre of standard always yellow at base; sweetly and pleasantly scented; height of flower 1.9-2.2 cm, length 1.7-2.0 cm. Bracts early deciduous; upper lip of calyx entire or 2-toothed at tip, lower lip entire and slightly longer. Pods downy, 7-10 cm long, 1.8-2.4 cm wide, with 4-6 large seeds. Seeds smooth and shiny, ovoid to slightly compressed, white, sometimes with brown markings, or brownish black in dark blue or purple flowered strains, 7-10 mm long, 6-8 mm broad. Strains also exist with slightly smaller pods and seeds.

Distribution—Originally from the mountainous regions of Peru, where it is cultivated to a limited extent for its seed. Grown in gardens; sometimes known as the "pearl" lupin. Seed of this species has also been received under the name *L. pantelericus* (accession N. 1996).

(ii)—**L. luteus** Linn., Sp. Plant. 721 (1753)

A rather spreading herbaceous annual 0.2-1.0 m tall, branching strongly from the base, covered with sub-appressed hairs 1-2 mm long. Leaflets 7-11, usually 8-9, oblong-obovate to linear-obovate, appressed hairy on both sides. Inflorescence 10-25 cm long on a peduncle 5-12 cm long. Flowers verticillate in rather distant whorls, bright golden-yellow, with a strong pleasant sweet scent; length and height of flower both about 1.6 cm; pedicel short, about 2 mm. Bracts obovate, deciduous; upper lip of calyx very deeply 2-partite, lower lip subequal, 3-toothed; bracteoles linear. Pods hairy, 5-6 cm long, 1.2-1.5 cm wide, with 4-6 seeds. Seeds smooth, compressed, 6-8 mm long, 5-7 mm wide, whitish with brown to black mottling, rarely almost black, or white in some improved varieties.

Distribution—Naturally occurring on sandy soils in the Western Mediterranean area: Tunisia, Algeria, Spain, Portugal, Corsica, Sar-

* In addition, the two species *L. varius* and *L. hirsutus* will be described from the literature, since although they are not known to occur in Australia they have in the past been confused with species which do. Apart from these two, descriptions are from populations of living material. Specimens are to be lodged with the W.A. State Herbarium.

dinia, Sicily and Italy. Widely and increasingly cultivated throughout Northern Europe: Holland, Sweden, Germany, Poland and Western parts of the U.S.S.R.; also in South Africa, New Zealand and Florida, on sandy soils for soil improvement and stock feed. Occasionally cultivated in Australia in gardens or very rarely for green manure. Naturalised in a few places south of Perth.

(iii)—**L. pilosus** Murr. in Linn., Syst. Veg. Ed. 13: 545 (1774)

A moderately branching annual reaching 0.4-1.0 m, stems densely covered with long silvery hairs 3-4 mm in length (plate 1, 1). Leaflets 9-11, obovate-oblong, about 3 times as long as broad, softly appressed-hairy on both surfaces. Inflorescences 20-30 cm long, subtended by a peduncle of 3-7 cm. Pedicel only a little shorter than calyx. Flowers verticillate, large, 2.0 cm long and 2.2-2.3 cm in height, dark blue; centre of standard white from base to upper margin, becoming deep purple with age; or flowers pink or white; faintly scented, scent spicy rather than sweet. Bracts lanceolate, deciduous; bracteoles linear-oblanceolate, 4-5 mm long, 1 mm or more broad. Upper lip of calyx deeply 2-partite; lower lip longer, entire. Pods hairy, 5-8 cm long, 2.0-2.5 cm wide; seeds 2-4, usually 2-3, very large, 1.1-1.4 cm long, 1.0-1.2 cm broad, moderately compressed, very rough, mottled brownish-red with a broad blackish-red crescent around the hilum.

Distribution—Native or naturalised, comparatively rare, in Southern France, Corsica, Sardinia, Sicily, Greece, Palestine, Syria and Tunisia. Cultivated to a small extent in Europe, probably mainly as an ornamental plant. Occasionally seen in Western Australia in or escaped from gardens. Not to be confused with the American species *L. villosus* Willd., which is sometimes known as *L. pilosus* Walt.

(iv)—**L. digitatus** Forsk., Flor. Aegypt-Arab. 131 (1775)

L. cosentini Guss., Flor. Sic. Prod. 2: 398 (1828)

L. hirsutus Sieber ex Guss., Flor. Sic. Prod. 2: 399 (1828)

L. forskahlei Boiss., Diagn. Plant. Orient. (1) 9: 10 (1849)

L. pilosus Murr. ssp. *cosentini* (Guss.) Fiori, Nuov. Flor. Anal. Ital. 805 (1925)

L. pilosus L. ssp. *digitatus* (Forsk.) Zhuk., Bull. Appl. Bot. & Pl—Br. 21: 263 (1929)

Similar to preceding species. Annual, rather bushy, 0.2-1.4 m in height. Stems and petioles covered with fine short erect white hairs, mostly about 1 mm or slightly less (Plate 1, 2). Leaflets 9-11, oblanceolate-oblong, 3.4-3.8 times as long as broad (except for earlier leaves, which are relatively shorter and broader), softly appressed-hairy on both surfaces. Inflorescences usually 10-20 cm long, subtended by a short peduncle, up to 4 cm. Flowers verticillate, smaller than in preceding species, 1.5-1.7 cm in length, 1.8-1.9 cm in height, blue, with centre of standard yellowish white becoming purple with age; but white spot not extending to tip of standard as in *L. pilosus*; or flowers very rarely white, pale pink, or pale blue; not scented. Pedicel one-third length of calyx or less. Bracts lanceolate, deciduous; bracteoles linear, about 4 mm long and up to 1 mm wide; upper lip of calyx deeply 2-partite; lower lip longer, 3-toothed, 2-toothed or entire. Pods hairy, 4.5-6.0 cm long, 1.5-1.7 cm wide. Seeds 3-5, usually 4, 8-9 mm long, about 7 mm broad, moderately compressed, not more than half the size of those of preceding species, rough, mottly brown with blackish-brown markings, including a narrow crescent around the hilum.

Distribution—Occurs naturally in Portugal, Southern Italy, Sicily and Corsica, and common as a weed in fields of the Nile Valley. Cultivated in Palestine, and perhaps elsewhere in the Eastern Mediterranean region (?). Naturalised in Western Australia along a 400 mile coastal belt of sandy soils from north of Geraldton to south of Busselton, and there cultivated for sheep feed and soil improvement. Present also in South Australia.

(v)—**L. angustifolius** Linn, Sp. Plant. 721 (1753)

L. varius Savi, Fl. Pisan. 2: 178 (1798)

Annual; growth habit very erect, with profuse rather fine lateral branching, reaching 0.4-1.5 m; densely leafy; stems and petioles with sparse fine appressed hairs not more than 1 mm long. Leaflets 7-9, linear, dark green, glabrous above, appressed-hairy beneath. Inflorescence almost sessile; flowers alternate, 1.4-1.5 cm long, 1.2-1.4 cm in height, blue tinged with purple, particularly at tip of wings, or rarely pale blue, pink, pale pink, purple or white; not scented. Bracts oblanceolate-obovate, deciduous; bracteoles short, oblong. Upper lip of calyx rather short, very deeply 2-partite; lower lip much longer, entire or slightly 2-3-toothed. Pods 5-6 cm long, 1.5-1.6 cm wide; seeds 4-5, smooth, ± spheroidal, 6-8 mm long and 5-6 mm wide, slate-grey with brown marbling and whitish spots, or rarely white, brown, black or intermediate colours.

Distribution—Native to almost every country bordering the Mediterranean. Widely cultivated in Holland, Sweden, Germany, Poland and the U.S.S.R.: also in South Africa, New Zealand and Florida, for soil improvement and latterly for stock feed. In Western Australia cultivated as a green manure crop and for sheep feed; also naturalised in the Swan Valley, near Perth, and southwards.

(vi)—**L. albus** Linn., Sp. Plant. 721 (1753)

L. termis Forsk., Fl. Aegypt.-Arab. 131 (1775)

L. sativus Gater., Desc. Pl. Montaub. 26 (1789)

L. varius Gaertn., Fruct. 2: 324 t. 150 (1791)

L. bivonii Presl., Fl. Sic. 1: 24 (1826)

L. hirsutus Eichw., Casp. Cauc. 23 (1833)

L. thermis Gasp. in Atti. Acc. Nap. 6: 229 t. 10 (1851)

L. thermus St. Lag. in Ann. Soc. Bot. Lyon 7: 129 (1880)

An upright annual, 0.4-1.6 m in height, branching at flowering from base of peduncle; sparsely covered with white silky hairs 1-2 mm in length and ± appressed. Leaflets 5-7 or 7-9, oblong-obovate, glabrous or glabrescent above, silky-hairy below, with ciliate margins. Inflorescence almost sessile; flowers alternate, sometimes approaching sub-verticillate towards apex of inflorescence, 1.6-2.0 cm long, white variably tinged with purplish blue, particularly on the wings; not scented. Bracts early deciduous; bracteoles small or absent; upper lip of calyx entire, lower lip entire or slightly 3-toothed. Pods large, 8-12 cm long, 2.0-2.5 cm broad; seeds 4-6, 0.9-1.4 cm long, ± square, compressed, with a smooth surface and yellowish white in colour.

Distribution—Occurs in wild form in countries bordering the Mediterranean and in Ethiopia. Cultivated in these regions and in Argentina, Central Europe and parts of Southern U.S.S.R. as a grain legume. Very rare in Western Australia, but occasionally grown in districts near Bunbury.

(vii)—**L. hartwegii** Lindl. in Bot. Reg. 25 t. 31 (1839)

L. bilineatus Benth., Pl. Hartw. 11 (1839)

Erect growing annual, covered with long (3-7 mm) silvery hairs, 0.6-0.9 m in height, branching little until approaching flowering and then from well up the stem: stem stout, slightly hollow. Stipules long, 2-4 cm, linear-awl-shaped, hairy. Leaves a light green colour. Leaflets 7-9, oblong-oblanceolate, hairy below, glabrous or nearly so above. Raceme up to 40 cm long, subtended by a very stout peduncle, and forming pods the whole way up. Flowers large, verticillate to alternate, not falling readily, dark blue, or pale blue, purple, pale purple or white; only faintly scented; height of flower 2.0-2.2 cm, length 1.9-2.1 cm. Bracts conspicuously long, linear, about twice the length of the fully developed bud, very hairy, deciduous. Calyx hairy, with linear bracteoles, upper lip entire to fairly deeply 2-partite, lower lip entire. Pods long and narrow, 4-6 cm long, 0.6-0.8 cm broad, with 7-10 seeds. Seeds small, 4.5 mm long, 3 mm broad, smooth, compressed, colour varying with that of flowers.

Distribution—A native of Mexico. Grown in gardens and known as the Hartwig or Hartweg lupin.

(viii)—**L. pubescens** Benth., Pl. Hartw. 169 (1844)

Dwarf to medium-sized annual, height 0.2-0.6 m, bushy, branching strongly from near base; covered with short fine hairs up to 1 mm in length. Stipules awl-shaped, 3-4 mm long. Leaflets 5-9, oblong-oblanceolate, finely hairy below, glabrous or with sparse hairs above, margins finely ciliate. Inflorescence 10-30 cm long, or only up to 10 cm in dwarf-growing varieties, subtended by a peduncle 4-12 cm long. Flowers verticillate to sub-alternate, usually blue to pink or pale pink with a pleasant sweet scent similar to that of *L. mutabilis*, 1.3-1.6 cm in height, 1.4-1.6 cm in length. Bracts lanceolate, early deciduous; calyx shortly furry, upper lip 2-partite or sometimes entire, lower lip entire. Pods 3-5 cm long, 1.1-1.4 cm broad; seeds 4-6, smooth, small, ovoid to oblong, 4-6 mm long, 3-4 mm broad, colour varying from white to dark brown.

Distribution—Native to Mexico and Guatemala, and widely cultivated for ornamental purposes.

Bailey (1949) states that a large number of the smaller cultivated annual lupin varieties are classified under *L. pubescens*, but that undoubtedly many of these are derived from interspecific crosses, natural or artificial. They are sometimes known as *L. hybridus*, and include the varieties *albococcineus*, *atrococcineus*, *californicus*, *dunnetti*, *duplex*, *elegans* and *tricolor* (these two probably from *L. pubescens* × *L. polyphyllus* crosses), *guatemalensis*, *hybridus roseus*, *insignis moritzianus*, *pulcherrimus*, *speciosus*, *succulentus*, *superbus*, *venustus*. *L mutabilis* may enter into the ancestry of some, and perhaps other species as well. Inevitably, therefore, the group is very heterogeneous. The above description covers only the very limited number of dwarf garden varieties commonly grown in Australia.

(ix)—**L. polyphyllus** Lindl. in Bot. Reg. 13 pl. 1096 (1827)

L. macrophyllus Benth. in Sweet Brit. Flow. Gard. 7 t. 356 (1836)

A tall erect perennial, reaching 1.0-1.6 m. Stems woody, sparsely hairy to glabrous. Stipules awl-shaped, hairy; petioles long; leaflets 9-17, oblanceolate, glabrous or sparsely hairy above, appressed-hairy beneath, margins ciliate. Inflorescences very long, up to 60 cm, on peduncles 3-8 cm long; flowers numerous, 1.2-1.4 cm long, subverticillate, on long pedicels. Bracts awl-shaped, early deciduous; calyx short, lobes entire or finely serrated. Flowers dark blue, or light blue, pink, violet, white, or yellowish. Pods 2.5-4 cm long, 0.7-0.9 cm wide. Seeds 5-9, smooth, small, oblong, about 4 mm in length, variously coloured and spotted.

Distribution—Native to the West Coast of North America, from California to British Columbia. Cultivated as a green manure crop in Northern Europe, and widely in cooler climates as an ornamental plant, for which purpose it is particularly fine.

According to Bailey (1949), many of the ornamental varieties, including the Russell lupins, Downer's hybrids, Harkness hybrids and others, are in fact derived from interspecific crosses. The various flower colour types of the Russell lupin are descended from a *L. polyphyllus* × *L. arboreus* cross.

(x)—**L. hirsutus** Linn., Sp. Plant. 721 (1753)

Fairly low-growing annual, 0.4-0.7 m, covered with long, spreading, rigid, rusty hairs. Leaflets 5-7, obovate-spatulate, coarsely hairy on both surfaces. Inflorescence short, oval, with upper flowers verticillate and lower ones alternate. Flowers blue, sometimes pink or white, corolla nearly twice as long as calyx; bracts awl-shaped, persistent; calyx bracteolate, upper lip deeply 2-partite, lower lip fairly deeply 3-toothed and twice as long. Pods densely rusty-hairy, with 3-4 seeds. Seeds smooth, greyish-brown with reddish spots and black lines on the margin.

Distribution—Native or naturalised in countries bordering the Mediterranean.

Gardner and Elliot (1929), and Gardner and Bennetts (1956) describe *L. hirsutus* as having been naturalised in Western Australia for many years, though probably restricted to the Geraldton-Northampton district, and as being known, together with *L. digitatus*, as the "West Australian blue lupin." The writer has never seen it, and samples of seed received from both the Western Australian Department of Agriculture and the C.S.I.R.O. Plant Introduction Section under the name *L. hirsutus* have all turned out to be in fact *L. pilosus*. It is probably the latter species to which Gardner refers, although his descriptions are clearly of the true *L. hirsutus*.

(xi)—**L. varius** Linn., Sp. Plant. 721 (1753)

L. sylvestris Lam., Fl. Franc. 2: 627 (1778)

L. semiverticillatus Desr. in Lam. Encycl. Meth. 3: 623 (1791-2)

A rather low-growing hairy annual. Leaflets very hairy on the lower surface but glabrous or glabrescent above. Flowers alternate at the base of the inflorescence but verticillate towards the top; corolla blue or rose, with a white spot on the standard. Upper lip of calyx 2-toothed only, lower lip slightly 3-toothed. Pods hairy, with 4-5 seeds. Descriptions of the seeds are contradictory.

Distribution—Native to the Iberian Peninsula and the Balaeric Islands, and said to be sometimes grown in gardens in Central Europe.

Key to Lupinus Spp. in Western Australia

(a)—Seeds large, > 6 mm long; agricultural or ornamental species
- (b)—Leaves and stems glabrous; ornamental . . . . (i) *L. mutabilis* Sweet
- (b)—Leaves and stems sparsely to densely hairy
  - (c)—Flowers verticillate or almost so
    - (d)—Flowers golden yellow; seeds smooth . . . . (ii) *L. luteus* Linn.
    - (d)—Flowers not yellow; seeds rough
      - (e)—Lower lip of calyx entire; hairs on stem about 3-4 mm long; seeds > 1 cm long, mottled reddish brown; pods with 2-3 seeds (iii) *L. pilosus* Murr.
      - (e)—Lower lip of calyx often, but not always, 3-fid at tip; hairs on stem up to about 1 mm long; seeds < 1 cm long, dirty brown; pods with 3-5 seeds (iv) *L. digitatus* Forsk.
  - (c)—Flowers mostly alternate, seeds smooth
    - (d)—Leaflets linear, seeds ± spheroidal (v) *L. angustifolius* Linn.
    - (d)—Leaflets oblong-obovate; seeds ± square, com-compressed, white (vi) *L. albus* Linn.

(a)—Seeds small, < 6 mm long, smooth; ornamental species only
- (b)—Leaflets 5-9; annuals
  - (c)—Erect habit, with long hairs (3-7 mm); bracts twice as long as the fully developed bud . . . . (vii) *L. hartwegii* Lindl.
  - (c)—Bushy dwarf or semi-dwarf habit; finely hairy; bracts shorter than fully developed bud . . . . (viii) *L. pubescens* Benth.
- (b)—Leaflets 9-17; perennial (ix) *L. polyphyllus* Lindl.

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7.—Pyroxenic Granites and Related Rocks in the Jerramungup-Calyerup Creek Area, Western Australia

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The coarse porphyritic pyroxenic Jerramungup Adamellite makes a sharp contact with unusual hypersthene granulites at Calyerup Creek. Not far from this contact large angular blocks of Jerramungup Adamellite occur as xenoliths in the even-grained biotitic Calyerup Granodiorite. A chemical analysis and some petrological data of rock types at Calyerup Creek are recorded and comparisons are drawn with the porphyritic pyroxene adamellite from the type area at Jerramungup. Monazite, fluorite and anatase occur in the Calyerup Granodiorite. Clinopyroxene, hornblende and biotite are the femic minerals in the Jerramungup Adamellite at Calyerup Creek, but hypersthene occurs in addition in the type area about 5½ miles to the N.W. The mineralogy of the basic clots in the porphyritic adamellite suggests that they are much-modified micro-xenoliths derived from metasomatized country-rocks not known in the area. The Jerramungup Adamellite and Calyerup Granodiorite are formally named.

Introduction

A narrow belt of about 1,000 feet of clean outcrop in the Calyerup Creek was mapped and a brief reconnaissance of the neighbourhood undertaken in January, 1950.

The purpose of this paper is to record some of the evidence for the magmatic emplacement of the Calyerup Granodiorite and some unusual mineralogical and petrological features of this and some associated rocks.

Calycrup Creek is a non-perennial saline watercourse which joins the Gairdner River about 5½ miles south of Jerramungup homestead which is about 280 miles by road S.E. of Perth and 27 miles E. of Ongerup on the Ongerup-Ravensthorpe road. The outcrops described in this paper occur where (in January, 1950) the Quaalup-Jerramungup track crossed the creek known as Calyerup Creek 7 miles S.E. of Jerramungup (measured along the track). There are many good outcrops in the neighbourhood, especially in the valley of the Gairdner River.

Mineral Compositions

The following graphs were used:—plagioclase—Winchell and Winchell (1951, p. 283, Fig. 176), orthopyroxene—Poldervaart (1950, p. 1076, Fig. 3), clinopyroxene—Hess (1949, p. 634, Plate 1).

Terminology

"Magma" is used of a mass which has moved into its present position, either wholly liquid or as a mobile crystal mush. *Adamellite* and *granodiorite* are used as in Hatch, *et al.* (1949).

Structure

The map (Fig. 1) clearly shows that the even-grained biotitic Calyerup Granodiorite has been emplaced magmatically into the coarse porphyritic pyroxenic Jerramungup Adamellite. There has been no obvious macroscopic corrosion of the xenoliths of Jerramungup Adamellite by the Calyerup Granodiorite, but basic xenoliths show considerable signs of assimilation (e.g., 31291, † p. 37). The foliation due to flowage of smaller lenticular basic xenoliths is obvious near the large angular xenoliths of Jerramungup Adamellite. Elsewhere the Calyerup Granodiorite is fairly homogeneous, even-grained and massive.

The varying trend of foliation from block to block of the angular xenoliths of Jerramungup Adamellite demonstrates movement of the blocks. It should be remembered, however, that such movement could have taken place at the time of brecciation of the adamellite and not necessarily at the time of active injection. The strong streaming foliation in the younger granite near the xenoliths suggests, however, that the brecciation, rotation of the blocks, and injection were pene-contemporaneous. The evidence from the small area which was mapped suggests that the brecciation was controlled by N.-S. subhorizontal shear (W. block N.) and granite injection was controlled by much reduced stresses acting in a similar sense.

Sharp contacts of the coarse porphyritic Jerramungup Adamellite and a somewhat migmatized hypersthene-biotite-andesine granulite were noted less than 100 yards upstream from the eastern edge of the map. Although there was no time to make a detailed study of the contact, it would appear that the development of some of the features of the granulite was due to the emplacement of the Calyerup Granodiorite (see p. 36). It is hoped that these notes will encourage a detailed study of the good outcrops of metamorphic rocks in Calyerup Creek.

Petrology

Meta-sediments

Hypersthene-quartz-biotite-andesine granulite (31289).—Greywackes have been strongly metamorphosed to form a coarse hornfels or granulite near the contact with porphyritic pyroxenic adamellite (31288).

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† Numbers refer to specimens housed in the Department of Geology, University of Western Australia.

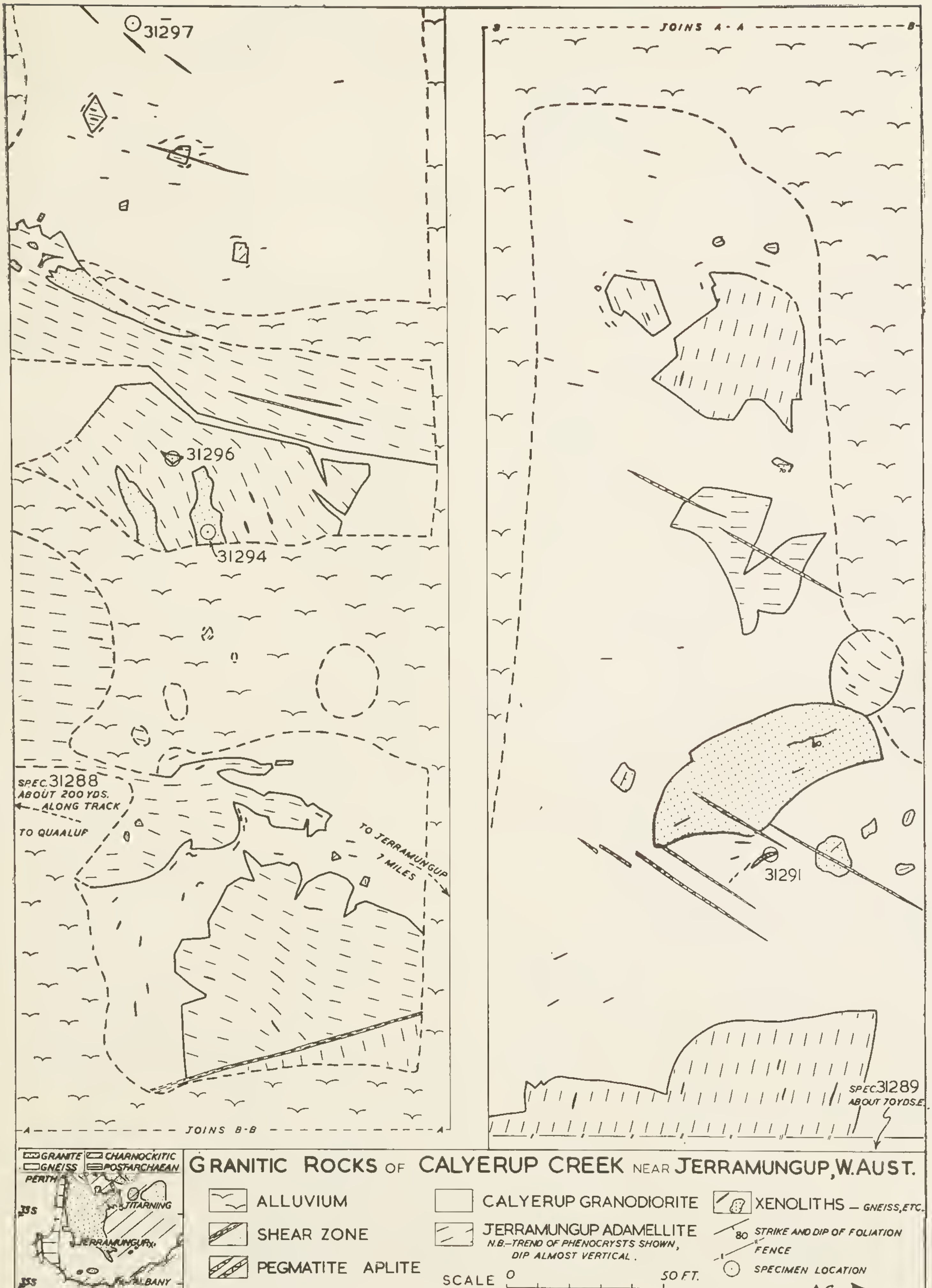
31297
31296
31294
SPEC. 31288
ABOUT 200 YDS.
ALONG TRACK
TO QUAALUP
TO JERRAMUNGUP
7 MILES
JOINS B-B
JOINS A-A
31291
SPEC. 31289
ABOUT 70 YDS. E.
GRANITE
CHARNOCKITIC
GNEISS
POSTARCHAEAN
PERTH
TITARNING
JERRAMUNGUP
ALBANY
33S
35S
117E
119E
GRANITIC ROCKS OF CALYERUP CREEK NEAR JERRAMUNGUP, W. AUST.
ALLUVIUM
SHEAR ZONE
PEGMATITE APLITE
CALYERUP GRANODIORITE
JERRAMUNGUP ADAMELLITE
N.B.—TREND OF PHENOCRYSTS SHOWN, DIP ALMOST VERTICAL.
SCALE 0 50 FT.
XENOLITHS — GNEISS, ETC.
80 STRIKE AND DIP OF FOLIATION
FENCE
SPECIMEN LOCATION
N

Fig. 1.

Specimen 31289 is a dark grey, fine to medium-grained, dense rock in which poor original bedding planes are not readily recognised except in thin-section. The rock is fairly homogeneous except where cut by occasional narrow migmatitic veins. The micro-texture is banded granulose with a rude orientation of biotite parallel to the bedding. Most minerals are between 0.25 mm and 0.3 mm in diameter. The main minerals are as follow:—

Andesine (about 50%): anhedral and equidimensional; albite and pericline twins; extinction $\perp a$, $\alpha' \wedge (010)$ $+ 21^\circ$ indicating An_{38}.

Biotite (about 20%): pleochroism, α = straw yellow, γ = reddish brown, with prominent pleochroic haloes; sensibly uniaxial (-ve.); β = 1.642 ± .003.

Quartz (about 15%): anhedral and equidimensional non-strained grains.

Hypersthene (about 15%): anhedral equidimensional grains; strongly pleochroic with α = pink, β = pale fawn, γ = pale green; 2 Vα = 60° ± 2°; γ = 1.707 ± .003, indicating about Of_{32}.

Zircon and *monazite* occur as small anhedral grains, commonly as cores of pleochroic haloes in biotite, and *pyrite* and *apatite* are uncommon accessories.

In a small acidic vein which cuts the rock the following minerals are developed:—

Quartz, andesine, cordierite (showing pleochroic haloes and some pinitization), *biotite* and rare large *hypersthene* grains.

The biotite and hypersthene both occur in large grains and are of the same type as in the main rock where they appear to be stable together. In the vein the cordierite appears to be stable with both hypersthene and biotite. Cordierite has not been found in any other rock of the area. It is the apparent stability of cordierite and hypersthene (with biotite) that would suggest that this rock belongs to the pyroxene-hornfels metamorphic facies rather than to the granulite metamorphic facies. The proximity of two intrusions has caused great complications and a proper metamorphic study must await more detailed mapping and sampling. However, since the biotites of both the country-rock and the Calyerup Granodiorite are very similar in all respects it would appear that the formation of biotite and the development in the vein of the cordierite and coarse hypersthene were controlled by the emplacement of the Calyerup Granodierite and not by the porphyritic pyroxene adamellite.

The granitic rocks at Calyerup Creek

Coarse porphyritic hornblende-salite-biotite adamellite (a facies of the Jerramungup Adamellite)—(31288).—This specimen (31288) was collected 20 yards N.W. of the gate approximately 250 yards S.S.E. from Calyerup Creek crossing on the Jerramungup-Quaalup track, and was selected as typical of the Jerramungup Adamellite in the Calyerup Creek area. It is coarse-grained, light grey, granitic rock with about 20% of subhedral phenocrysts of pink microcline which are set in a matrix mainly of white plagioclase and femic minerals. Although platy-flow structure is not pronounced it is measurable.

In thin-section the texture is typically granitic with average diameter of matrix femic minerals about 1 mm and matrix felsic minerals about 2 mm. Some of the more significant characteristics of the minerals are as follow:—

Microcline (about 30% of rock): Phenocrysts (mostly 3 cm long) make up about 20% of the rock; commonly twinned (Carlsbad); a pale pink fluorescence is exhibited under short-wave ultra-violet radiation (cf. Wilson 1950); similar microcline (about 10% of rock) is in the matrix where it corrodes plagioclase and forms ragged micro-antiperthite.

Oligoclase (about 35% of the rock): confined to the matrix where commonly it is heavily corroded by microcline, resulting in ragged and irregularly distributed micro-antiperthitic inclusions; extinction $\perp a$, $\alpha' \wedge (010) = + 3^\circ$, indicating An_{22}; some myrmekitic growths on edges of grains.

Quartz (about 19% of the rock): undulose extinction.

Biotite (about 10% of the rock): pleochroism, α = brownish yellow, γ = dark brown; sensibly uniaxial (-ve.); β = 1.651 ± .002; appears to be corroded by hornblende; shows alteration to *chlorite* and *sphene* in places.

Clinopyroxene (2.6%): important constituent of basic clots; pale green and almost non-pleochroic; β = 1.697 ± .001; 2Vγ = 56° ± 2°; composition is approximately Wo_{47} En_{34} Fs_{19}, indicating a *salite*.

Amphibole (2.4%): large poikilitic grains (up to 4 mm long) enclosing biotite, clinopyroxene, apatite, and magnetite; pleochroism, α = yellowish fawn, β = khaki-green, γ = deep green; γ = 1.686 ± .002; 2Vα = 55° (approx.).

The accessories make up about 1% of the rock. The most important are *fluor-apatite* (which is abundant as subhedral grains in the femic clots), *sphene* (mostly as sparse ragged fawn-coloured growths in chloritized biotite, and rarely as a narrow rim around ilmenite), *zircon* (murky pinkish brown, euhedral crystals which are non-fluorescent under short-wave ultra-violet radiation), *ilmenite* and *magnetite*, rare meta-mict (?) allanite and very rare *monazite*.

There is abundant evidence that the plagioclase and quartz have been shattered, impregnated and partly replaced by microcline. The femic clots may represent reconstituted microxenoliths of the country-rocks, but it should be observed that, as far as is known, the biotite and pyroxene of the immediately adjacent country-rocks have no resemblance to the biotite and pyroxene of the adamellites.

Xenoliths in the coarse porphyritic adamellite.—Many lenticular and partly assimilated xenoliths are common in both the coarse porphyritic adamellite and the even-grained Calyerup Granodiorite. It is not intended to present detailed descriptions of the xenoliths, but some of the more important petrological features of two of them are outlined immediately below.

(i) *Hypersthene-biotite-oligoclase-microcline-quartz granulite (31294).*—This faintly banded fawn-brown rock shows an orientation of much-chloritized hypersthene and biotite. There are irregular poikiloblasts of clinopyroxene and hornblende enclosing the other minerals which are commonly 0.3 mm in diameter. The quartz shows undulose extinction. The plagioclase is poorly twinned and the microcline is not markedly micro-perthitic. The biotite and hornblende resemble those of the host-adamellite.

(ii) *Salite-biotite-microcline-quartz-oligoclase granulite (31296).*—This greyish-fawn rock, with an average grain-size of 0.4 mm diameter, shows an orientation of the biotite (pleochroic, α = fawn, γ = dark brown). The clinopyroxene (and, to a less extent, hornblende) occurs as large irregular poikiloblastic masses. The biotite, clinopyroxene and hornblende are almost identical with those of the host-adamellite.

The orientated hypersthene grains in 31294 suggest that these granulites belong to the granulite metamorphic facies. The absence (as far as can be determined by study of crushings of the rock) of orthopyroxene from the porphyritic adamellite is notable in that orthopyroxene is found in the country-rock (e.g., 31289) and in many xenoliths. The growth (as poikiloblasts) of clinopyroxene and hornblende of types so similar chemically to those of the host-adamellite indicates that the rock as a xenolith must have reached a grade of metamorphism equivalent to a high level of the amphibolite facies.

Biotite granodiorite (the Calyerup Granodiorite)—(31297).—This specimen, which was collected approximately 250 feet downstream from the Calyerup Creek crossing, is to be considered the type-specimen of the homogeneous granodiorite which intrudes the Jerramungup Adamellite and other rocks of the area. The trend of flow-structure is only measurable with confidence where the occasional lenticular xenoliths of biotite schist occur. The trend is approximately a few degrees E. of N. The Calyerup Granodiorite is thought to be of Precambrian age. The rock is mostly even-grained with grains about 1.8 mm in diameter, but there are a few phenocrysts of microcline up to 10 mm in length.

In thin-section the texture is typically granitic. Some of the more significant characteristics of the minerals are as follow:—

Oligoclase (40.7%): extinction $\perp a$, $\alpha' \wedge (010) = +7\frac{1}{2}°$ (with negligible zoning) indicating An_{25}; ragged and irregularly distributed micro-antiperthitic inclusions of microcline; albite twinning and pericline twinning.

Quartz (28.0%): undulose extinction.

Microcline (18.5%): fresh (less kaolinized than plagioclase which it commonly corrodes); almost negligible micro-perthite; cross-hatch twinning.

Biotite (11.6%): pleochroism, α = light yellowish fawn, β = dark orange-brown, γ = very dark brown; sensibly uniaxial (-ve.); β = 1.649 $\pm$ .002; some *chloritization* (chlorite: length slow; β = 1.626 but variable); prominent pleochroic haloes around monazite and zircon; apparently random orientation of grains.

Fluor-apatite (0.4%): colourless and non-fluorescent (short wave U.V.); euhedral and subhedral grains; small cores of darker (?) apatite not rare.

Iron ores (0.5%): mostly concentrated in the femic clots; *magnetite, ilmenite* (commonly leucoxenized) and *pyrite* (which may be surrounded by magnetite or *haematite*).

Monazite (0.1%): resinous yellow; rounded, and some grains have a thin alteration crust; 2V γ approximately 10°; identity confirmed by spectroscope (Wilson 1958*b*).

Zircon: small, colourless, euhedral crystals up to 0.15 mm long; elongate bubble- and mineral-inclusions common; zoned; some radioactive as shown by some of the haloes in biotite; fluorescence nil (short-wave U.V.).

Fluorite: uneven blue grains found only in rock-crushings.

Anatase: (P. E. Playford, who made some preliminary observations on this specimen, was the first to discover the anatase) orange-brown, highly refringent and strongly doubly refracting, slightly pleochroic, minute euhedral prismatic crystals in (and apparently restricted to) chlorite which is formed by alteration of ilmenite and biotite.

Calcite, epidote, (?) allanite, muscovite, and *lawsonite* are very rare accessories. Orthopyroxene and amphibole are absent.

Plagioclase, most of the quartz and possibly some of the biotite would appear to have formed prior to emplacement of the granodiorite. Microcline, and some quartz and biotite have corroded and "healed" the strained crystal mush, and volatile-rich material and hot waters at a late stage have produced much of the monazite, chlorite, anatase, fluorite, calcite, lawsonite and haematite.

An *analysis* of this rock appears in Table I as No. 5. The analysis, norm and mode show that this rock is actually between granodiorite and adamellite in composition. There is no obvious chemical similarity between this rock and the Jerramungup Adamellite.

Xenolith in the Calyerup Granodiorite (31291).—This is a very dark grey coarse very basic hornfels composed of hornblende, hypersthene, clinopyroxene, biotite and quartz. The hornblende poikiloblasts include both pyroxenes

and there is a tendency for the biotite to show a preferred orientation. The biotite is similar in colour and type to the biotite of the hypersthene-quartz-biotite-andesine granulite of the country-rock (see p. 36) but is much different from the biotite of the porphyritic pyroxene adamellite. The growth of the biotite and possibly the cordierite and coarse hypersthene in the country-rock thus may be due to metamorphism by the granodiorite and not by the adamellite.

The granitic rocks at Jerramungup

Coarse porphyritic hypersthene-biotite-salite-adamellite (the Jerramungup Adamellite)—(31303).—A brief description of this rock, collected by the author from an excellent exposure in the Gairdner river close to the old Jerramungup homestead, was included by Prider in an earlier paper (Clarke, *et al.* 1954, p. 45). A chemical analysis and more mineralogical data are now available, but Threadgold's excellent modal analysis is retained. The analysis of this rock appears in Table I as No. 1.

Specimen 31303 is a coarse porphyritic rock containing 35% (by volume) of pink euhedral microcline phenocrysts (up to 4 cm long) in a mesocratic coarse matrix of white oligoclase, dull green pyroxene, brown biotite, colourless quartz and pink microcline. The phenocrysts fluoresce a rose-pink under short-wave ultraviolet radiation (cf. 31288 from Calyerup Creek, and see also Wilson 1950). In outcrop the phenocrysts are alined with strike approximately 340° (but strike is variable in the area) and dip 75° W. Numerous narrow micro-granitic dykes trending roughly E.N.E. cut the adamellite, and thin-section study shows that the microcline phenocrysts commonly enclose large irregular relics of oligoclase, clots of clinopyroxene, orthopyroxene, magnetite, biotite and quartz. The phenocrysts, therefore, are not the first crystals to form in the mass which later became the "magma." The author suspects the phenocrysts grew in the matrix (at the time either solid, or a crystal mush) during the early stage of the emplacement of the "magma." In any case, they were soon in a relatively fluid mass, and sufficiently well-formed to resist deformation (but contrast the deformed grains of plagioclase), yet platy-flow structure was able to develop. Indeed, it would seem that during phases of the emplacement many variable rock types could be formed either by solidification of potassic material removed from time to time by filter-press action, or by solidification of the residues at various places and times. It is thought significant that numerous narrow micro-granitic dykes (trending roughly E.N.E., i.e., normal to the regional flow-alinement of the phenocrysts) cut the adamellite near the Jerramungup homestead. For several years, the author has thought that a filter-press mechanism may be responsible for a comparable association of porphyritic granites and micro-granitic rocks in the Dale Bridge area near York (Wilson 1952, pp. 216-217, and 1958*a*). The Jerramungup Adamellite is thought to be of Precambrian age.

Some of the main petrographic data for the rock are as follow:—

The phenocrysts of microcline (35% of the rock) are up to 4 cm long, plagioclase is commonly 6 mm long and individual grains of femic minerals and quartz are mostly somewhat more than 1 mm long.

Oligoclase (40.3% of rock, 60.7% of matrix): mostly confined to the matrix where it is commonly much corroded by microcline or impregnated by microcline to give ragged and irregularly distributed micro-antiperthitic inclusions, but there are numerous relics within the microcline phenocrysts; extinction $\perp$ *a*, $\alpha' \wedge (010) = +5\frac{1}{2}°$ for some relics in microcline phenocrysts and it ranges from $+3°$ to $+7°$ elsewhere in the matrix, thus indicating a variation in apparently unzoned grains from An_{22} to An_{26}; chloritization and saussuritization have developed along some albite twin-planes adjacent to serpentinized hypersthene; may be separated from corroding microcline by myrmekite.

Microcline (38.0% of rock, 6.7% of matrix): large phenocrysts up to 4 cm long, small irregular grains in the matrix and micro-antiperthitic inclusions in oligoclase; severely replaces oligoclase (q.v.); weakly microperthitic.

Clinopyroxene (7.3% of rock, 11.0% of matrix): pale green almost non-pleochroic; $\beta = 1.697 \pm .001$; $2V\gamma = 54\frac{1}{2}° \pm 1°$; composition is approximately Wo_{45} En_{35} Fs_{20}, indicating a *salite;* a major constituent of the femic clots, and commonly rims orthopyroxene which is less stable to hydrothermal activity and is heavily serpentinized.

Quartz (5.6% of rock, 8.5% of matrix): majority of grains show undulose extinction but some associated with symplectic growths of biotite are unstrained.

Biotite (5.6% or rock, 8.5% of matrix): pleochroism, α = straw-yellow, γ = red-brown, and with pleochroic haloes around zircon and small grains of (?) monazite; sensibly uniaxial (-ve.); $\beta = 1.640 \pm .002$; mostly associated with clinopyroxene but may be found in symplectic intergrowth with unstrained quartz.

Orthopyroxene (1.4% of rock, 2.1% of matrix): occurs in femic clots as relict patches included in fibrous chloritic masses impregnated with magnetite dust; pleochroism weak, α = very pale reddish brown, γ = very pale green; $2V\alpha = 54\frac{1}{2}° \pm 1\frac{1}{2}°$ ($55° - 55\frac{1}{2}°$, uncorrected for hemispheres with n = 1.649) indicating hypersthene about Of_{37}; R.I. (γ) difficult to measure because of alteration products, but with γ = 1.695 (approx.) the mineral would seem to be bronzite (note: for γ = 1.695, 2V should be about 70° not $54\frac{1}{2}°$ as determined); consequently, the composition is in doubt, but *hypersthene* (say, about Of_{35}) is favoured.

Iron ores (1.3% of rock, 2.0% of matrix): mostly in form of irregular grains of magnetite in the femic clots; secondary magnetite dust is common with the altered hypersthene.

Other accessories (0.5% of rock) are *fluorapatite* (plentiful as subhedral grains in the femic clots), *zircon* (radioactive nuclei of haloes in biotite; mostly murky fawn-coloured subhedral grains; strongly zoned with cores of darker granules of zircon, or opaque granules), *hornblende* and *monazite*.

The source of the basic clots and xenoliths, both of which may contain orthopyroxene and clinopyroxene, is uncertain. No geological mapping of the area has been done, but the nearest outcrop of pyroxene-bearing metamorphic country-rocks (so far as is known) is near Calyerup Creek some 5½ miles S.E., but at the contact the coarse porphyritic adamellite (31288) is both devoid of orthopyroxene and more siliceous.

Although it is suspected that the orthopyroxene (and clinopyroxene) of these adamellites is related to charnockitic rocks in the vicinity (see Wilson 1958*a*: map), it should be pointed out that the orthopyroxene of similar Central Australian "igneous rocks" (which from most of the evidence seem to have a similar palingenetic origin) is significantly different from the orthopyroxene of the country rocks. In Central Australia, where there was less difficulty in establishing the compositions of the pyroxenes, these phenomena were carefully documented (Wilson 1954*a*, p. 15, but especially 1954*b*, pp. 173-180). There would appear to be a fundamental reconstitution of the pyroxenes (and some other minerals) during mobilization of the country-rocks. In the Jerramungup area, however, there is as yet no evidence of the ferriferous orthopyroxenes which seem to appear in most pyroxenic "granites."

The physico-chemical condition which presumably would allow the country-rocks to become mobilized may be expected to be different (e.g., in content of H_2O, O, F, P, etc.) from those prevailing in the country-rocks, even though temperature and pressure may be sufficiently high to allow the formation of mineral assemblages which are comparable to those of the granulite metamorphic facies.

The name, Jerramungup Adamellite, is formally given to the pyroxenic rock described above. By some strict definitions the rock could be called a monzonite, for the analysis (Table I) shows less than 65% SiO_2, and both normative and modal quartz are less than 10%. However, an over-all average composition of the porphyritic "granite" of the whole Jerramungup area appears to be that of a typical adamellite (as seen, for instance, at Calyerup Creek where 19% quartz occurs in 31288).

The analysis, norm and mode of the porphyritic Jerramungup Adamellite (Table I, No. 1) are set out for comparison with those of other porphyritic granites, viz., the Everard Adamellite from Central Australia (No. 2), the Albany Adamellite from the south-coastal regions of Western Australia (No. 3) and a typical granite from the Wheat Belt region of Western Australia, the porphyritic adamellite from near Jitarning (No. 4). A more detailed review of the composition of Western Australian granites is being published elsewhere (Wilson 1958*a*).

TABLE I

Granites from Calyerup and Jerramungup

	1	2	3	4	5
SiO_2	62·08	65·17	66·90	64·76	65·54
TiO_2	0·54	0·56	0·63	0·97	0·58
Al_2O_3	15·94	17·34	14·76	13·99	15·78
Fe_2O_3	0·76	1·60	0·32	2·07	1·02
FeO	3·56	2·09	5·01	3·52	3·90
MnO	0·08	0·18	0·12	0·27	tr.
MgO	2·88	0·49	0·93	1·41	1·92
CaO	4·32	3·35	2·46	3·86	2·63
BaO	...	0·19		0·12	
Na_2O	3·56	3·48	2·42	3·42	3·33
K_2O	5·12	5·43	5·04	3·46	3·62
H_2O+	0·58	0·10	0·93	0·59	1·02
H_2O-	*nil*	0·05	0·08	0·03	0·09
P_2O_5	0·51	0·23	0·21	0·47	0·17
CO_2	*nil*		*nil*	0·16	0·20
	99·93	100·26	99·81	99·89*	99·80
	C. I. P. W. Norms				
qtz.	8·50	15·93	23·88	21·48	22·37
o'clase	30·23	32·08	29·47	20·43	21·34
albite	30·11	29·34	20·44	28·96	28·17
anorth.	12·38	15·54	11·40	13·13	10·79
corund.		0·04	1·22		2·44
diop. wo	2·50	....	....	2·65	
diop. en	1·40	...	...		
diop. fs	1·00				
hyp. en	5·77	1·20	2·30	5·86	4·78
hyp. of	4·14	1·91	7·92		5·36
mag.	1·11	2·32	0·46	2·99	1·48
ilmen.	1·03	1·06	1·22	1·83	1·11
apat.	1·21	0·54	0·34	1·11	0·40
pyrite	.		. .	0·49 calc.	= 0·45
	Modes (Volume %)				
qtz.	5·6	17	K-fel.	olig.	28·0
K-fel.	38·0	35	andes.	qtz.	18·5
plag.	40·3	39	qtz.	K-fel.	40·7
o'pyr.	1·4	—	biot.	biot.	—
c'pyr.	7·3	1	horn.	horn.	—
amphib.	tr.	4	ores	ilmen.	—
biot.	5·6	0·5	sphene	epid.	11·6
ores	1·3	3	calc.	apat.	0·5
apat.	0·3	0·5	apat.	zois.	0·4
S.G.	2·785†	2·685†	2·701†	2·77	2·694†

1. Porphyritic pyroxene adamellite (the Jerramungup Adamellite) (31303), Jerramungup, W. Aust. Anal., W. H. Herdsman.
2. Porphyritic hornblende adamellite (the Everard Adamellite) (30265), Umgulbullarinna Rock Hole, Everard Ranges, C. Aust. (Wilson 1954*b*, p. 119).
3. Porphyritic adamellite (the Albany Adamellite) (30974), Mt. Melville, Albany, W. Aust. (Clarke, *et al.* 1954, p. 43).
4. Porphyritic adamellite, Res. 12096, 86 mile peg No. 2 Rabbit Proof Fence, near Jitarning, W. Aust. Anal., H. P. Rowledge.
5. Biotite granodiorite (the Calyerup Granodiorite) (31297), Calyerup Creek, near Jerramungup, W. Aust. Anal., W. H. Herdsman.

* Includes FeS_2 = 0.49, V_2O_3 = 0.30, ZrO_2 = tr, Cr_2O_3 = nil.

† S.G. accurate to ± 0.002.

Conclusions

Petrographic studies would suggest that the coarse porphyritic pyroxenic granites of the Jerramungup-Calyerup Creek area were formed by a reconstitution and feldspathization of basic

rocks. In several parts of the area (e.g., Calyerup Creek) there are highly granitized xenoliths containing large porphyroblasts of microcline similar to the "phenocrysts" of the host rock. However, the gneisses and metasediments at the eastern contact contain no porphyroblasts. This suggests that the porphyritic granites may have been formed by a metasomatic process at a considerable depth. The Everard Adamellite from Central Australia is very similar in this respect.

The shattering of part of the Jerramungup Adamellite has allowed numerous granite and microgranites to be emplaced. In the Calyerup Creek area the Calyerup Granodiorite (possibly a differentiate from the parent Jerramungup Adamellite "magma") may have been emplaced during or soon after the shattering and random jostling of the blocks of porphyritic adamellite.

Acknowledgments

Transport for the field work was made available by the late Mr. H. T. Phillipps, and the cost of the two chemical analyses was borne by research funds from the University of Western Australia. Messrs. P. E. Playford and I. M. Threadgold (then senior students) made thin-sections and some preliminary laboratory observations on two of the rocks (31297 and 31303, respectively).

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Notice

The West Australian Museum

Mr. L. Glauert, B.A., F.G.S., F.R.Z.S., retired from the directorship of the Museum at the end of 1956 after 47 years of service to the institution. At the age of 78 he is a remarkably active man and still continues his herpetological research within the Museum. The stimulating part played by Mr. Glauert in encouraging the development of many aspects of biological science in W.A., both in his official capacity and privately, was recognised by the W.A. Natural History Society who published a *Festschrift* in his honour (W.A. Naturalist Vol. 5 No. 7, 1957).

Dr. W. D. L. Ride, Mr. Glauert's successor, took up his appointment as Director in July 1957. Appropriately enough his special research interest has been the systematics and functional anatomy of the macropod marsupials, for which he was recently awarded the D. Phil. (Oxon.). His appointment follows closely the establishment of the W.A. Museum and Art Gallery Trust as a body separate from the Public Library and many changes are taking place in the Museum. During the year 1957-58 a number of new appointments have been made both on the scientific and technical side and minor structural alterations are being made to provide laboratory space for the additional staff.

Dr. G. F. Mees has been appointed as Curator and is expected to arrive from Holland in June, 1958. He is at present Assistant at the Rijksmuseum van Natuurlijke Historie, Leiden and has collected extensively for that and other institutions, both in the West Indies and in Netherlands New Guinea. He has published a number of papers in two fields; on the behaviour, systematics and anatomy of fish, and on the systematics of birds, particularly the Zosteropidae.

Mr. R. George, B.Sc., a graduate of the University of W.A., has been appointed Assistant Curator. While serving in the C.S.I.R.O. Division of Fisheries and Oceanography, he spent several years studying the biology of the crayfish *Panulirus longipes* in the coastal waters of W.A. Mr. George joined the Museum staff at the beginning of May, 1958.

Two further scientific appointments have been made: Mr. R. P. MacMillan, D.F.C., B.Sc., as Research Entomologist and Miss Kaye Vollprecht, B.Sc., as Scientific Assistant to the Director. Mr. MacMillan is at present studying polymorphism in the Buprestidae, jewel beetles that are particularly well represented in W.A. Miss Vollprecht has been concerned especially with sorting and cataloguing the valuable Tennant collection of fossils which has not previously been accessible. In this there are many fine specimens of great interest to Western Australian geologists.

A number of new appointments to the technical staff has made possible considerable reorganisation of the collections. The large mineral gallery is temporarily closed to the public while the study collection is re-housed separately from the displays. This will make the collection more accessible for research and provide better facilities for the public displays. During 1957 the United Services Institution presented to the Trust a large collection of arms and other war relics that had previously formed their war museum, housed in the Swan Barracks. This fine collection resulted largely from the personal efforts of Col. G. F. C. Wieck, D.S.O., O.B.E., who was director of the museum. Funds were provided by the W.A. Government to house this collection, and an Arms and Armour gallery is now nearing completion that will provide both display and storage space for this collection and for similar material already in possession of the Trust.

During 1956 a small research laboratory was constructed in order to provide facilities for visiting scientists and it has already been used for short periods by both overseas and Australian workers. In spite of the present overcrowded conditions it is hoped that many more will be welcomed at the Museum in the future.

A considerable amount of laboratory space has been gained by reorganisation of storage, and by minor reconstruction, although the old gaol buildings still have to be used for display, storage, and staff accommodation despite their manifest unsuitability for the purpose. It was with great satisfaction that the Trust welcomed the announcement that the Government will provide additional permanent buildings for the Museum and Art Gallery and that building will start shortly of a new block to cost about £180,000. This will house the administrative staff, provide additional storage, library and laboratory space and also a lecture theatre to seat about 250 persons. It is hoped by the Trust that various scientific societies will avail themselves of the facilities this theatre will offer and make it their regular meeting place.

E. P. Hodgkin.

8.—The Tides of South-Western Australia

By E. P. Hodgkin* and V. Di Lollo*

Manuscript received 17th October, 1956.

An account is given of the chief characteristics of the tides at the ports of Fremantle, Geraldton, Bunbury, and Albany. The tides are mainly of daily type and of small range (maximum about 3 ft at Fremantle and 4 ft at Albany). When the declination of the moon exceeds about 10° the tides are always of daily type; but tides of semidaily type occur for several successive days in each tropic lunar cycle when the moon is near zero declination and the sun near the equinox.

Sea level varies both with atmospheric (wind and barometric pressure) and hydrologic conditions (water temperature and salinity); the extreme range of daily sea level is about 4 ft at Fremantle—greater than the maximum tidal range. Monthly sea level is generally about one foot higher in winter than in summer, but there is much variation from year to year.

Introduction

The tides of the coast of south-western Australia are in many respects unusual. They are generally daily, with only one high and one low water in each 24 hours, and with low water at about the same time on successive days, but getting gradually earlier through the year; the daily range of the tide is small, so small that meteorological and hydrological forces produce changes in sea level of the same order of magnitude. As a result long range predictions of height of tide are of little value and are therefore not published. These facts are not generally known locally and it is commonly assumed that, despite their small range, the tides behave in the same general way as on the coasts of northern Europe.

The main characteristics of the tides are of course well known to those concerned with shipping and the maintenance of port installations. Tydeman (1948) in his "Report on Port of Fremantle," states: "For the purpose of port construction and operation, Fremantle may be regarded as tideless. The range of movement of the sea is small and generally is little more than in the Mediterranean, generally referred to as tideless. The normal advantages of tides in port operation and construction cannot be employed owing to the smallness of tidal range, a disadvantage at Fremantle." Again: "Thus, unlike most ports, tides at Fremantle follow no fixed law and are irregular and unpredictable." These statements are sufficient from the point of view of the harbour authority because, as stated above, height of tide cannot be predicted with sufficient accuracy to make it worth while publishing tide tables. Nevertheless the tidal, that is the periodic, water movements do follow known laws, and both time and range of tide can be predicted with reasonable accuracy.

Curlewis (1915) described the tides at Fremantle and Port Hedland; he stressed the apparent irregularity of the Fremantle tides and the influence of the weather on them, but showed that they "depend to a large extent on the moon's declination, and from its position the range of tide may be gauged fairly accurately." He calculated harmonic constants* for both ports and records these together with others obtained previously. Bennett (1939) analysed the 1933 records and prepared graphs by means of which it is possible to "predict" height of high and low water, provided barometric pressure is known. Such predictions are generally accurate to within half a foot. He also gives a graph showing percentage time of exposure at different levels. Both accounts are incomplete in certain respects and some of the data have been misinterpreted.

The present paper is an attempt to set down succinctly what are the tidal movements on the south-west coast and what are believed to be the causes of these movements. It is based on a study of the tide records from the ports of Fremantle, Geraldton, Bunbury, and Albany for a number of years. This study was begun in an attempt to explain the discrepancies between "predicted" and actual water movements, however a much fuller analysis will be necessary before quantitative data can be given relative to the influence of weather on the tides.

Definition: "Range of tide" here means the difference in vertical height between highest and lowest water levels reached in any 24-hour period. Mean ranges have been calculated on this basis. In the use of other terms we have followed Marmer (1951), except that an arbitrary distinction has been made between tides of daily and semidaily type for the purpose of estimating the relative numbers of each (page 46).

Causes of the Tides

Tides are raised by the combined gravitational forces of the moon and sun attracting the water of the oceans. These forces set up oscillations within the various ocean basins in phase with the movements of the moon and sun relative to the rotating earth. The tidal ebb and flow at any particular place is the resultant of the position of the place in the oscillating system, the physiography of the ocean floor, the shape of the coastlines, and the size of the basin. These tidal water movements are modified

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* figures that define the constituents of the tides and from which it is possible to predict the tides.

locally by meteorological and hydrological forces; e.g., by the winds, which blow the water on to or away from the shore; by changes in air pressure, raising or lowering the water surface; and by variations in the density of the sea water caused by water temperature and salinity.

Full accounts of the tides and of tidal theory will be found in Marmer (1926), Doodson and Warburg (1941), or Russell and Macmillan (1952). Dates and times of occurrence of lunar and solar phenomena mentioned here will be found in the annual publication "The Nautical Almanack" (H.M. Stationery Office, London).

The gravitational tide-producing forces have periods that are approximately semidaily, daily, or half a month or more (long-period forces). At any particular place, or at a particular phase in a long-period cycle, (a) semidaily forces may be dominant and cause the tides to be of semidaily type, with two high waters and two low waters in each period of apparent revolution of the moon (24.8 hr), (b) daily forces may be dominant and cause tides of daily type with only one H.W. and one L.W. in each day (24 hr), or (c) the two components may be about equal and the tides of mixed type with two H.Ws and two L.Ws of markedly inequal height. There is no sharp distinction between these three types of tide and intermediate conditions are observed. All three types of tide are illustrated in the record shown in Fig. 1: semidaily tides on 9th to 10th March, daily tides from 28th to 31st, and mixed tides on 21st and 25th.

The following are the principal astronomic influences that determine the nature of the tides.

(i) The different periods of apparent rotation of the sun (24 hr) and moon (24.8 hr) about the earth cause the moon to appear successively: in the same direction as the sun (new moon), at 90° to it (first quarter), on the opposite side of the earth (full moon), again at 90° (last quarter), and back to new moon. This is the synodic month, with a period of approximately 29½ days.

When the moon is full or new the gravitational attractions of the two bodies supplement one another and tidal ranges of semidaily tides are increased (spring tides), at first and last quarter the attractions oppose one another and the tidal ranges are decreased (neap tides). Thus there are two maxima and two minima in each synodic cycle.

(ii) The moon revolves around the earth in an ellipse from perigee (shortest distance) through apogee (greatest distance) and back to perigee. This is the anomalistic month, with a period of approximately 27½ days.

When the moon is at perigee tidal ranges are increased, when at apogee they are decreased. There is only one maximum and one minimum in each cycle.

(iii) The plane of the moon's orbit is inclined to the plane of the earth's equator, and the moon is successively: at maximum declination north, above the earth's equator (zero declination), at its maximum declination south, above the equator, and back to maximum declination north. This is the tropic month, with a period of approximately 27⅓ days.

When the moon is at maximum north or south declination the daily component of the tide is always greater, tending to produce tides of daily type. When the moon is approaching zero declination the semidaily component is normally greatest, tending to produce tides of semidaily type. Tides occurring near maximum declination are "tropic" tides and those occurring near minimum declination are "equatorial" tides. There are two maxima and two minima in each tropic cycle, the intervals between successive equatorial tides being 12 to 15 days.

The angle of inclination of the moon's orbit to the earth's equator varies from a maximum of 28½° to a minimum of 18½°. This is the nodal cycle, with a period of 18.6 years. As a result the magnitude of the daily component also varies; this was least in 1941, increased to the maximum in 1950 and will decrease again until 1958.

(iv) The plane of the earth's orbit around the sun is similarly inclined to the plane of the earth's equator at 23½°. The sun is successively: at maximum declination south (soltice, about December 22nd), over the equator (equinox, March 21st) at maximum declination north (solstice, June 22nd), over the equator (equinox, September 23rd), and south again. Period one solar year.

At the solstices the daily component of the tides is reinforced; at the equinoxes the semidaily component is reinforced.

The effect of these and other minor modifying forces on the tides at any particular place differs with latitude and coastal topography. On the north-west coast of Australia, as in most parts of the world, the semidaily component is dominant and the tides are of semidaily type. There is a regular succession of spring and neap tides following the phases of the moon, and the range of these is augmented at the equinoxes producing the equinoctial or "king" tides.

On the coast of south-western Australia however the daily tidal component is dominant and the tides are mainly of the daily type; there is generally only one H.W. and one L.W. each day, and tides of semidaily type only persist for 3 or 4 days at a time when both the lunar and solar semidaily components are near their maximum. Tidal range is greatest near maximum lunar declination (tropic tides) and least near zero declination (equatorial tides), and the tropic tides are greater at the solstices than at the equinoxes.

Tides of the West and South Coast

Fremantle

Tidal movements are recorded by a Bailey patent tide machine situated on the southern side of Fremantle harbour and near its entrance. Continuous records have been taken since 1897. Because the harbour is in the mouth of the Swan River estuary the gauge also records river

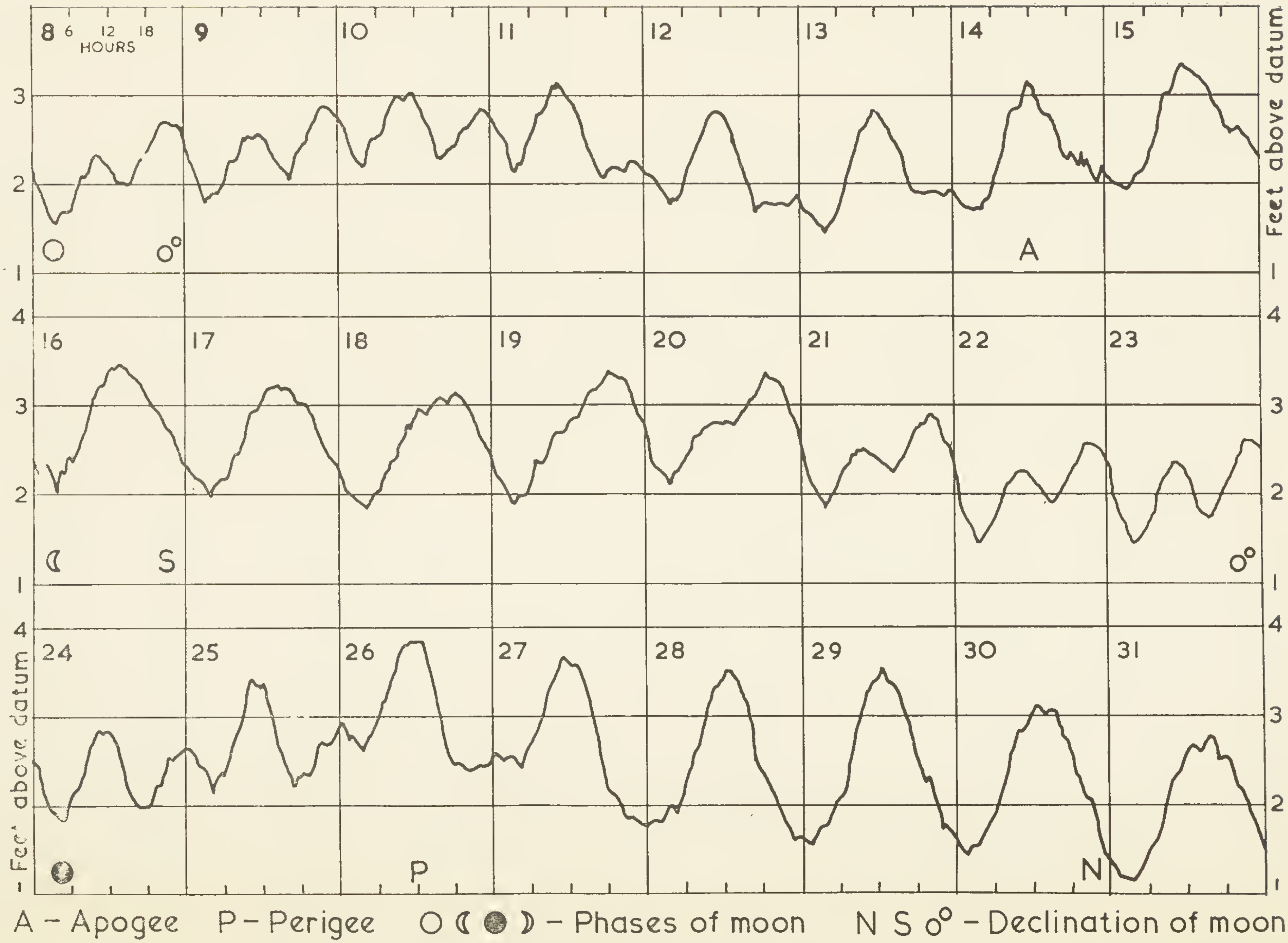

Fig. 1.—Fremantle tide record, March, 1955.

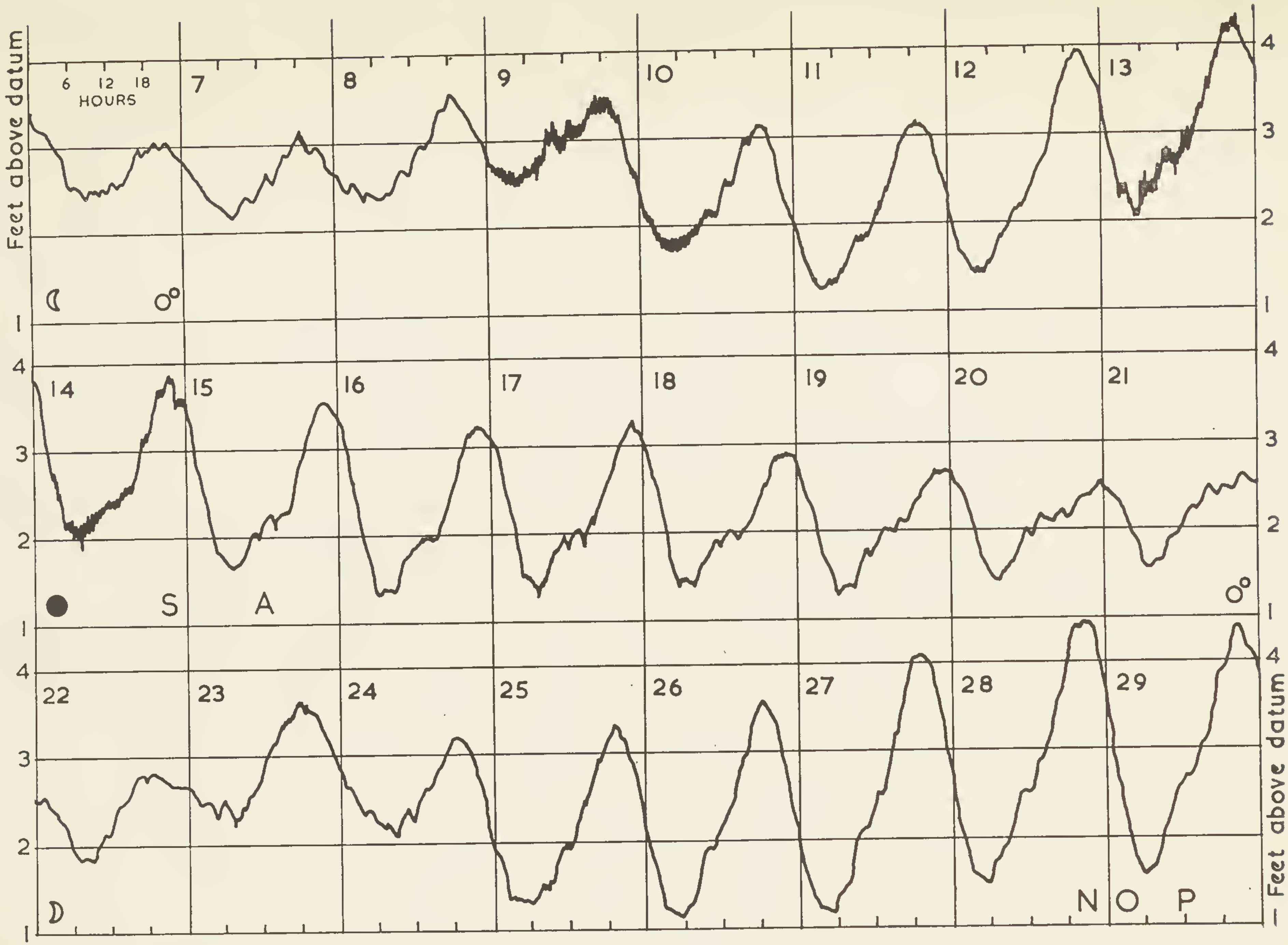

Fig. 2.—Fremantle tide record, December, 1955. For symbols see Fig. 1.

floods, but the influence of these is seldom great. Datum was fixed in 1892 by C. Y. O'Connor, then Engineer-in-Chief of the Public Works Department, at lowest low water, and levels on the gauge are relative to this; the tide very rarely reaches this level. The datum now accepted by the Australian Port Authorities Association is 0.3 ft above the gauge datum; this conforms to the definition of Indian Spring Low Water.

In preparing the following account we have given special attention to the records for the years 1913 and 1941, for which tide predictions were issued by the U.S. Coast and Geodetic Survey, and to the years 1949 to 1955.

Nature of the tide.—Typical tidal cycles, with the associated lunar phenomena, are shown in Fig. 1, from which the relation of the type to the tropic lunar cycle is evident. Tides of daily type with H.W. and L.W. about 12 hours apart occur near maximum declination, and tides of semidaily type occur near zero declination with two H.Ws and two L.Ws at about six-hour intervals. Between maximum and zero declination the tides change progressively and there are tides of mixed type, transitional in form between the typical daily and typical semidaily types. For the purpose of this investigation a somewhat arbitrary distinction has been adopted between the daily and semidaily types; a tide was regarded as semidaily if there were two high and two low waters within about 24 hours with a range exceeding 0.4 ft for a high-low sequence. This figure was adopted to avoid confusion between the smaller tides and the frequent minor oscillations which register up to 0.3 ft but seldom more. With a better damped instrument the second peak is identifiable when it has an amplitude of only 0.1 ft.

The number of days with tides of semidaily type in each tropic cycle varies with the declination of the sun. At the equinoxes there are from 4 to 7 each time the moon is near zero declination (13 to 15 in a calendar month); at the solstices there are usually none, and at zero lunar declination tides of daily type persist (Fig. 2). The mixed tides, whether at the solstices or at other times of the year, show vanishing tides; the water level stands for up to 12 hours near high or low water, and sometimes at intermediate levels (Fig. 1, March 12-13 and 26-27, Fig. 2, Dec. 21-22).

Range of tide.—The observed range of the tide also varies with the tropic lunar cycle; it is greatest at the tropic tides and least at the equatorial tides. The range in any one day seldom exceeds 3 ft, the maximum in 1955 was 3.2 ft on January 6th (actual ranges of tropic tides are shown in Table 2). Equatorial tides may have a range of only 0.5 ft and average 1.0 ft. The range of the daily tides increases towards the solstices, when the sun's daily component is greatest, and decreases towards the equinoxes (Table 1); the range of equatorial tides varies little through the year.

The range of the tide is also influenced to a lesser extent by the synodic and anomalistic cycles, so that the greatest tidal ranges are normally recorded when the moon is *at the same time:* (a) new or full (maximum synodic influence), (b) at perigee (maximum anomalistic influence), and (c) at maximum declination N. or S. (maximum tropic influence). Conversely, minimum ranges occur when the moon is at the same time (a) in its first or last quarter, (b) at apogee, and (c) above the equator. The reason for this will be clear from the statements on the causes of the tides.

The effect of these forces on the Fremantle tides does not appear to have been fully understood by earlier writers. Curlewis (1915) says: "Contrary to what might be expected the highest tide and greatest range happens when the moon is at its farthest North point, and not at its greatest South declination, when the moon would be almost directly over Fremantle, and would thus be in a position to exercise the maximum attractive force on the water." On the other hand, Bennett (1939) gives a graph which shows that the range of the tide is about 0.4 ft greater when the moon is at greatest declination south than when it is at greatest declination north.

The cause of this discrepancy lies in the fact that each author based his conclusion on the examination of the records for a single year. As stated above, the anomalistic month is 27½ days and the tropic month 27⅓ days. Consequently, throughout certain years, when the moon is at its greatest north declination it is also near perigee, and when it is at its greatest

TABLE I

Mean Monthly Range of Tide in Feet

Tropic lunar months	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	Means
Tropic Tides (means for 5-day periods)														
Geraldton, 1928–30	2·7	2·4	2·0	1·8	2·0	2·4	2·5	2·4	2·2	1·8	1·9	2·3	2·7	2·2
Fremantle, 1953–55	2·2	1·9	1·7	1·9	2·0	2·3	2·1	1·9	1·4	1·4	1·7	2·2	2·3	1·9
Albany, 1953–55	3·0	2·6	2·2	2·2	2·5	2·8	2·8	2·7	2·3	2·2	2·5	2·7	3·1	2·6
Equatorial Tides (means for 3-day periods)														
Geraldton	1·3	1·3	1·3	1·2	1·1	1·1	1·1	1·1	1·1	1·3	1·3	1·2	1·2	1·2
Fremantle	1·1	1·0	1·0	1·1	1·0	0·9	0·9	0·9	1·0	1·0	1·0	1·0	1·0	1·0
Albany	1·2	1·5	1·8	1·7	1·8	1·1	1·0	1·5	1·6	1·8	1·6	1·8	1·1	1·5

TABLE II

Range of tides at Fremantle.

Five-day periods about greatest lunar declination, when the moon is also at apogee or perigee. Figures show date, and range of tide in feet.

Declination of Moon	Moon at Apogee				Moon at Perigee			
	January	April	June	August	January	April	June	August
		1951				1955		
	(18) 1·6	(10) 1·6	(4) 2·0	(24) 1·2	(4) 2·0	(23) 2·1	(17) 1·8	(12) 2·3
	(19) 1·9	(11) 1·8	(5) 2·2	(25) 1·4	(5) 2·6	(24) 2·2	(18) 2·4	(13) 2·4
NORTH	(20) 2·0	(12) 1·8	(6) 1·9	(26) 1·2	(6) 3·2	(25) 2·1	(19) 2·9	(14) 2·8
	(21) 2·2	(13) 1·6	(7) 1·6	(27) 1·3	(7) 2·7	(26) 2·0	(20) 3·0	(15) 2·4
	(22) 2·0	(14) 1·7	(8) 1·7	(28) 1·6	(8) 2·7	(27) 1·8	(21) 2·6	(16) 2·0
Mean	**1·9**	**1·7**	**1·9**	**1·3**	**2·6**	**2·0**	**2·5**	**2·4**
		1955				1951		
	(18) 1·9	(10) 1·6	(4) 1·8	(24) 1·9	(5) 2·7	(23) 2·2	(17) 2·2	(11) 1·5
	(19) 1·8	(11) 1·5	(5) 1·7	(25) 1·1	(6) 2·7	(24) 1·9	(18) 2·5	(12) 2·0
SOUTH	(20) 2·2	(12) 1·5	(6) 1·9	(26) 1·2	(7) 2·9	(25) 2·4	(19) 3·2	(13) 2·3
	(21) 2·0	(13) 1·5	(7) 1·8	(27) 1·1	(8) 2·9	(26) 2·6	(20) 2·5	(14) 2·4
	(22) 2·3	(14) 1·4	(8) 1·6	(28) 2·0	(9) 2·4	(27) 2·4	(21) 2·6	(15) 2·7
Mean	**2·0**	**1·5**	**1·8**	**1 5**	**2·7**	**2·3**	**2·6**	**2·2**

Means: Moon at apogee .... 1.7 ft. Moon's declination north 2.05 ft. 1951 2.1 ft.
Moon at perigee .... 2.4 ft. Moon's declination south 2.15 ft. 1955 2.0 ft.

south declination it is also near apogee; after 4 to 5 years the opposite combinations occur. 1951 and 1955 were two such years. In Table 2 are shown the tidal ranges for the 5 days closest to greatest declination north and south in January, April, June, and August of these years. At these times the moon was also near the full or new. From this table it is clear that the tidal range was significantly greater when the moon was at perigee (2.4 ft) than at apogee (1.7 ft) irrespective of whether the moon was north or south of the equator.

Sea Level: Meteorological and hydrological factors.—While the maximum tidal range in any 24-hour period is only 3 ft, the extreme range from highest high water to lowest low water recorded over half a century is about 6 ft. The discrepancy between these two ranges is caused by the influence of meteorological and hydrological forces which produce changes in sea level of the same order of magnitude as the astronomic tides.

Offshore winds (those having an easterly component) tend to lower the water level, while onshore winds (with a westerly component) tend to raise the level of the water. The influence of the wind varies both with its strength and the angle at which it strikes the coast. The winds also affect the time of high and low water (see below).

High barometric pressure tends to lower sea level and low pressure to raise it. Bennett (1939) states that a rise of 1 inch in pressure causes a fall of 1.37 ft in water level. This figure appears to have been determined empirically for 1933 and differs from the theoretical value of 1.13 ft. It is in any case only an approximation since sea level is influenced not only by pressure at the place of observation, but by that over a considerable area of ocean.

The effect of weather conditions on sea level may be illustrated by the examples in Fig. 3. On May 26th and 27th, 1955, an extensive winter-type cyclone brought continuous westerly winds with a velocity of 25 to 30 knots which replaced the easterly winds of 24th, and the barometer fell from 30.2 in. to 29.4 in.; as a result sea level rose 2.1 ft from 2.6 ft (the mean value for the year) on 24th to 4.7 ft on 26th. The approach of the tropical cyclone of March 1956 caused a progressive rise in sea level from 2.0 ft above datum on 2nd to 3.3 ft on 4th. Both records show many minor oscillations, with a range (on this gauge) of up to about 0.3 ft and with a period of from about 15 minutes to an hour. These oscillations have various causes and may result from disturbances near the site of the gauge or at a distance of thousands of miles. The reason for the very low tides of December 1947 is not evident; the astronomical forces combined to produce maximum range tides (on 29th), but the winds and pressures recorded would not be expected to cause an abnormally low sea level. Variation in daily sea level is also evident in the two records reproduced in Figs. 1 and 2.

Figure 4 shows a marked seasonal shift in sea level, which tends to be about one foot higher in winter than in summer. The irregularity in the record and the marked differences from one year to another are however evident. Bennett (1939) ascribed this shift to the solar annual tide wave (Sa) and went on to say that, "it was directly proportional to the declination of the sun," the influence of which is semiannual. Neither the annual (Sa) nor the semiannual (Ssa) constituents of the tide are attributable to the very small astronomical forces with these periods. Curlewis (1915) says that, "the exceptional height often reached by the tides during the winter months is almost solely due to the banking up of the water against our western

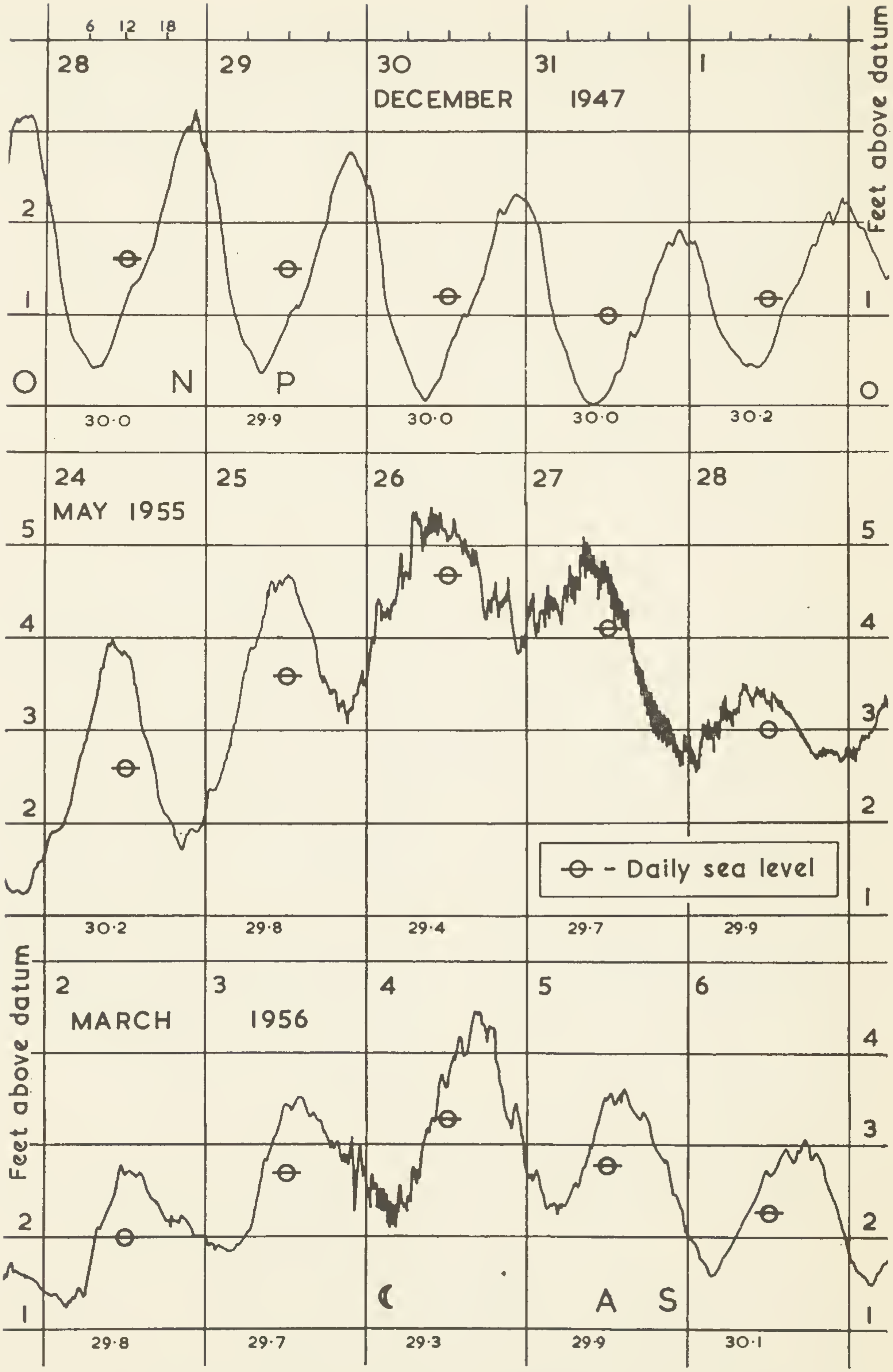

Fig. 3.—Fremantle tide record, to show influence of weather on sea level. Figures show barometric pressure in inches at 0900 hours. For symbols see Fig. 1.

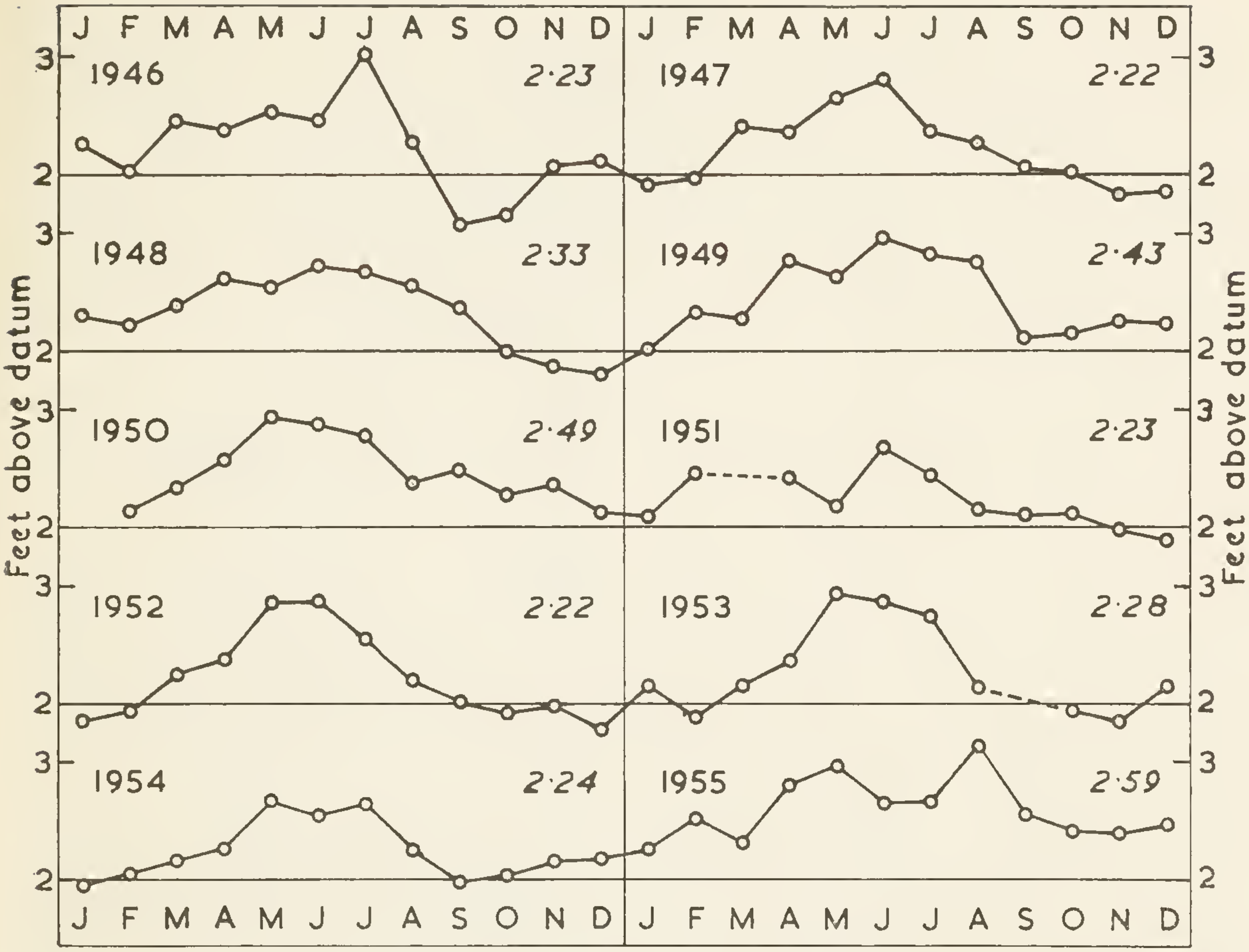

Fig. 4.—Monthly sea level at Fremantle, 1946-1955. Planimeter measurements by P.W.D., Perth.

coast line" by the westerly winds. Prevailing onshore winds tend to raise the sea level in winter and offshore winds to lower it in summer (Marmer, 1926). Mean barometric pressure varies little, but tends to be lower in summer than in winter so that this would cause the reverse effect to that observed.

Patullo *et al* (1955) attribute the shift mainly to changes in steric sea level, caused by water temperature and salinity at all depths (mainly temperature in these latitudes). Surface water temperatures are out of phase with the changes in level, maximum temperatures generally occur in March-April and minimum temperatures in September-October; however the scanty records available of water temperatures at 200 metres show the lowest figures in midsummer and the highest in midwinter (Rochford 1951 and 1953).

The seasonal shift must be presumed to be the resultant of the effects produced by these various forces, principally water temperature and prevailing winds.

Because of this fluctuation in sea level, the proportion of the time that any point in the intertidal belt is out of the water, or submerged, varies greatly through the year. Curves of percentage exposure for January and May 1954 are shown in Fig. 5; these were the months with lowest (1.94 ft) and highest (2.66 ft) monthly sea level. The extreme monthly levels during the ten-year period 1946-1955 were 3.13 ft (Aug. 1955) and 1.57 ft (Sept. 1946). Over shorter periods the range of level is of course much greater and daily sea level may lie anywhere between 5 ft and 1 ft above datum, when the curves are correspondingly higher or lower.

Mean sea level was calculated by N. J. Henry (MS. in Public Works Department, Perth) to be 2.480 ft above datum; the figure was later confirmed by the Liverpool Observatory and Tidal Institute. However it will be seen from Fig. 4 that even the annual M.S.L. is not constant from year to year, and in this ten-year period varies from 2.22 ft to 2.59 ft with a mean of 2.33 ft. The cause of these changes is not evident, they are presumably attributable to a combination of the meteorological and hydrological factors mentioned above.

Times of the tides.—From December to early April and from June to August the time of L.W. remains constant within two or three hours throughout each half tropic cycle (from one zero declination to the next). During the inter-

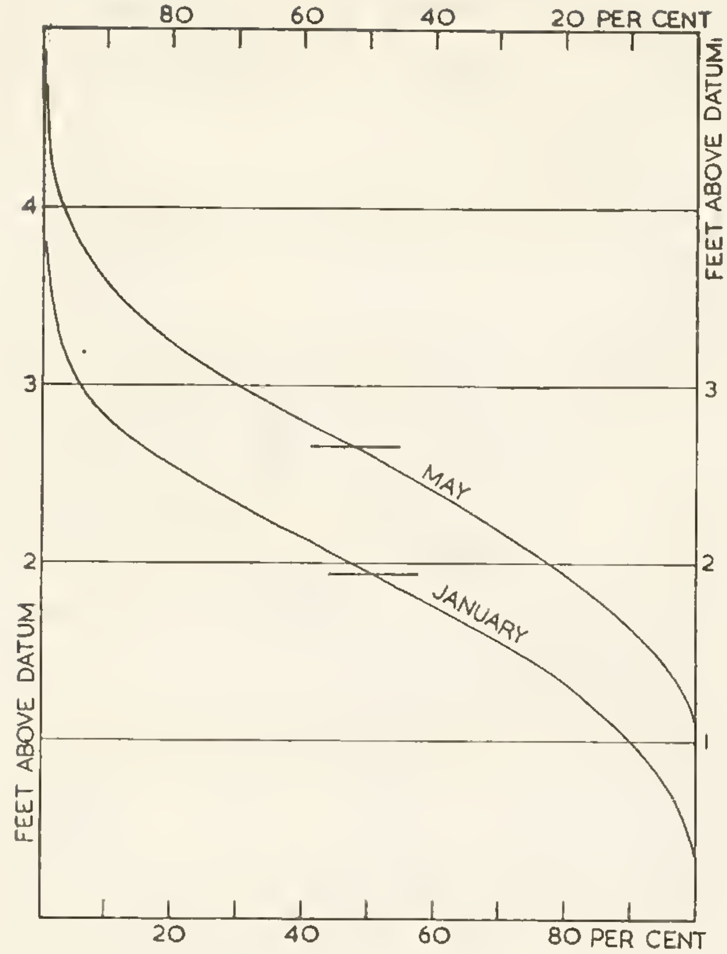

Fig. 5.—Percentage of time submerged or exposed at heights above datum. Fremantle, January and May, 1954.

vening months L.W. tends to show the more usual progression of 50 minutes later each day. The time of H.W. averages about 50 minutes a day later through each half cycle, but there is much variability and in some months it does not move more than 4 hours during a half cycle. Both H.W. and L.W. become earlier through the year. The predicted times of the tides in 1955 are shown in Fig. 6; they differ little from year to year. It will be seen that L.W. is in the early morning in summer and in the late afternoon in winter.

When equatorial tides are of semidaily type H.W. and L.W. succeed one another at six-hour intervals, while at tropic tides they are approximately 12 hours apart. From one series of tropic tides to the next the intervals between successive lows and highs may be almost anything from 6 to 18 hours (Fig. 1). From Fig. 1 it will also be noted that as one peak wanes at the equatorial tides a second waxes and replaces it.

The time of high and low water may be delayed or advanced up to two hours by strong winds. The time of H.W. is advanced by westerly winds and retarded by easterly winds; the time of L.W. is retarded by westerly winds and advanced by easterly winds, as compared with predictions.

The statements of Bennett (1939) with regard to the times of high and low water require modification, and predictions derived from his Fig. 6 are often up to 5 hours out.

Summary.—The tides at Fremantle vary with the tropic lunar cycle, which has a period of $27\frac{1}{3}$ days. When the moon is at its greatest declination N. or S. the tides are of daily type and have a maximum range of about 3 ft. at the solstices and $2\frac{1}{2}$ ft at the equinoxes (means for 3 years: 2.3 ft and 1.5 ft respectively). When the moon is near zero declination the tides have a mean range of 1.0 ft and a minimum of 0.5 ft; near the equinoxes these equatorial tides are of semidaily type for about five consecutive days, but near the solstices they are of daily type (often with one H.W. or L.W. and a prolonged period when the tide stands near the other extreme).

This pattern alters little with the changing phases of the moon, spring tides increase the range of the tides slightly and neap tides decrease them. Similarly the range is greater when the moon is at perigee than at apogee.

Superimposed on this regular predictable cycle are changes in sea level caused by variation in barometric pressure, in the strength and direction of the winds, and the temperature and salinity of the water. These may combine to cause a variation in daily sea level of about 4 ft, which is thus of the same order of magnitude as the small tidal range. Mean (monthly) sea level is nearly one foot higher in winter than in summer, but there is great variation from year to year.

The times of H.W. and L.W. are predictable; but they may be delayed or advanced by up to a couple of hours by the winds. During most of the year L.W. recurs daily at about the same time throughout any one lunar cycle, being in the early morning in summer and in the late afternoon in winter.

Geraldton.

An automatic recording gauge was operated here for about 15 years to 1930. The records for 1926 to 1930 have been studied.

The tides closely resemble those at Fremantle, being mainly of daily type, but with tides of semidaily type when the moon is near zero declination. Semidaily tides occur on from 10 to 12 days in each calendar month at the equinoxes, and from none to 1 or 2 near the solstices. The maximum tidal range at Geraldton is greater than at Fremantle, and tides of 3.6 ft range were recorded in January and June 1930. Equatorial tides also have a slightly greater range than at Fremantle and the minimum recorded in 1930 was 0.7 ft. Mean monthly ranges are shown in Table 1.

The datum now accepted for the port is 1.5 ft. below zero on the existing gauge. Monthly sea levels are shown in Table 3 and it will be seen that here, as at Fremantle, there is a seasonal shift with higher levels in winter and lower in summer.

Times of H.W. and L.W. at Geraldton are generally between 2 and 3 hours earlier than at Fremantle.

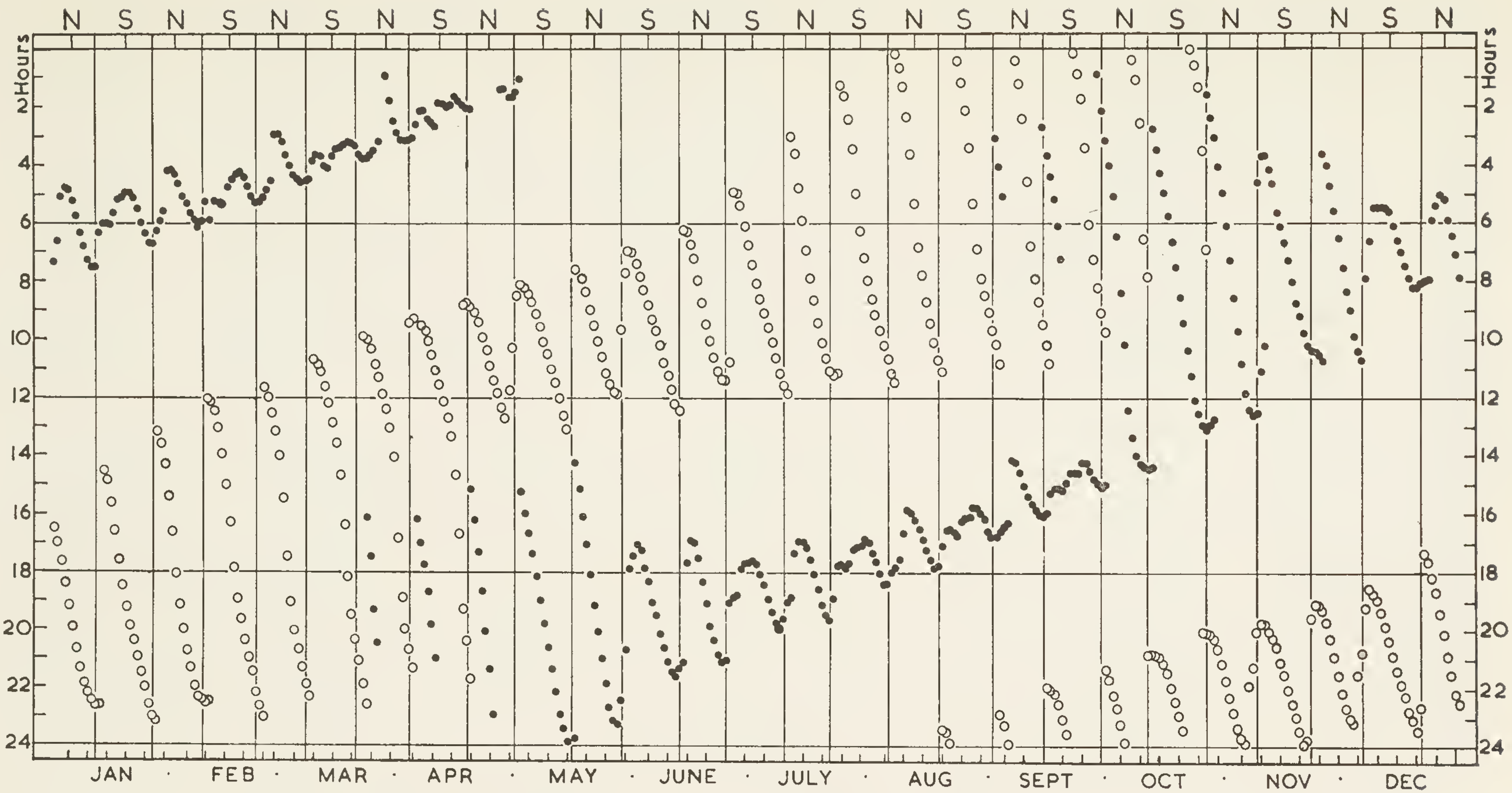

Fig. 6.—Predicted time of principal tide at Fremantle, 1955. Solid circles—Low water. Open circles—High water. Vertical lines—zero declination.

TABLE III

Monthly sea level, feet above datum (planimeter measurements)

	J.	F.	M.	A.	M.	J.	J.	A.	S.	O.	N.	D.	Mean
Geraldton, 1930	2·43	2·42	3·12	3·18	3·33	3·63	3·22	3·10	2·95	2·78	2·62	2·89	2·97
Fremantle, 1955	2·26	2·51	2·31	2·80	2·97	2·64	2·67	3·13	2·56	2·41	2·40	2·46	2·59
Albany, 1955	1·98	1·96	2·55	2·58	2·70	2·80	2·71	2·06	2·12	2·33	2·12	2·10	2·33

Bunbury.

An automatic recording gauge has been operated here since 1930. The 1955 record was compared with the Fremantle record for the same year; the two are very similar throughout. The daily range at Bunbury is only slightly greater than at Fremantle, but the extreme range is about 1 ft more.

The datum now accepted is 1.0 ft above zero on the gauge.

The times of H.W. and L.W. are up to about 1 hr later than at Fremantle.

Albany.

An automatic recording gauge has been operated here since 1952. The 1954 and 1955 records were studied and compared with the Fremantle records.

The tides at Albany have the same general character as those at Fremantle. Tides of semi-daily type are slightly more frequent, and near the equinoxes they last for 14 to 16 days in a calendar month.

The range of tropic tides is always greater than at Fremantle (about 0.7 ft); equatorial tides are of similar range to those at Fremantle at the solstices but 0.8 ft. greater at the equinoxes. The maximum range in 1955 was 3.9 ft on Dec. 28, the minimum 0.9 ft on June 14. Mean monthly ranges are shown in Table 1.

The setting of the zero on the gauge at Albany is accepted as true datum for the port. The seasonal shift in sea level shown by the monthly means given in Table 3 is of the same type as at Fremantle. The difference between highest and lowest monthly M.S.L. in 1955 was 0.84 ft.

Times of H.W. and L.W. at Albany may be up to about 2 hours later than at Fremantle. There is the same shift in the times of H.W. and L.W. through the year.

Tides on the North-West Coast

Although outside the scope of the present paper, a brief statement on the tides on the coast of Western Australia north of Geraldton is not out of place as it serves to emphasise the difference between the tides of the south-west and the tides of more usual type which occur on our northern coastline.

The available information is scanty and some of it is unreliable or open to misinterpretation. The best general sources are Chapman (1938) and the tide tables issued annually for Port Hedland. The following are the mean spring ranges given by Chapman.

Port Darwin	24 ft.
Wyndham	23 ft.
Collier Bay	36 ft.
Derby	34 ft.
Broome	28 ft.
Port Hedland	19 ft.
Cossack (Roebourne)	18 ft.
Fortescue	13½ ft.
Maud Landing	6 ft.
Carnarvon	5 ft.

These are substantially the same as the "spring rise" given in the tide tables because, datum is at about lowest low water. It should be noted that the figures for "neap rise" in the tables are also heights above datum and only a rough approximation to neap range can be gained from them. We are informed by Capt. G. D. Tancred, R.A.N., Senior Officer, Hydrographic Service, that the figure for spring range at Darwin should be 18 ft and that for Wyndham 24 ft.

It will be observed that from Roebourne northwards the tidal range is great, but that south of this port the range decreases rapidly.

Tide predictions are published for Port Hedland, where a recording tide gauge has been operated since 1913. The tides are of semi-daily type with a mean spring range of about 20 ft (1949: mean 20.7 ft, max. 24.1 ft, min. 17.2 ft) and a neap range in 24 hours of between 3 ft and 7 ft. Spring and neap tides follow from 1 to 3 days after the appropriate phases of the moon (data from tide tables). An account of the Port Hedland tides is given by Curlewis (1915).

At Onslow the tides are of similar type to those at Port Hedland, but the spring range is only 8½ ft, and neap range 1½ ft. Both height and time of tide may be considerably modified by weather conditions (information from Mr. A. H. Clark, Warfinger, Onslow). Predictions for Learmonth (courtesy of West Australian Petroleum Pty. Ltd.) show tides of similar type

and range; spring range averages 8 ft (1956: max. 8.6 ft, min. 7.0 ft) and neap range between 2 ft and 4½ ft. There is considerable diurnal inequality up to 2½ ft between the tides near maximum lunar declination.

At Carnarvon observations were made with a tide pole during daylight hours from November 1938 to November 1939. The tides are predominantly of semidaily type, but there are often tides of mixed type, and occasional tides of daily type from November to January. They follow closely the pattern of the Port Hedland tides, with the greatest range at spring tides a few days after full and new moon. However, the range is much smaller; spring range is about 4 ft, one fifth of that at Port Hedland, and neap range in 24 hours varies from 1 ft to 3 ft (mean 1.9 ft). Mean sea level varies considerably, presumably with atmospheric and hydrologic conditions, and in 1939 extreme H.W. was 6.0 ft and extreme L.W. 0.2 ft above datum. H.W. and L.W. are at about the same time as at Port Hedland (information from Public Works Department, Perth).

Conclusions

(i) On the coast of Western Australia, from north of Geraldton probably to the South Australian border, the tides are predominantly of daily type. Both type and range of tide change with the tropic (declinational) lunar cycle of 27⅓ days. "Tropic" tides, when the moon is near its greatest declination north or south, are always of daily type; while "equatorial" tides, when the moon is near zero declination, tend to be of semidaily type. The daily range of the tide is greatest near the tropic tides and least near equatorial tides (it is not correct to use the terms "spring" and "neap" for these maximum and minimum range tides).

The range of the tides is also influenced by the synodic and anomalistic lunar cycles; it tends to be greater at full and new moon than at first and last quarters, and at perigee than at apogee. These influences are however masked by the declinational effect.

(ii) Both type and range of tide also change with the sun's declination. Near the solstices there are few tides of semidaily type, none in December and June, while at the equinoxes they occur on from 10 to 16 days in each calendar month. Tropic tides have their greatest range near the solstices and least near the equinoxes; a maximum range of about 3.0 ft and 2.5 ft respectively at Fremantle.

(iii) Between the daily and semidaily tides near the equinoxes, and at equatorial tides near the solstices there are mixed tides intermediate in form between the daily and semidaily types. At these times, vanishing tides stand near high or low water for some hours, or at some intermediate level.

(iv) The type of the tides is essentially similar at all four ports studied (Geraldton, Fremantle, Bunbury, and Albany), except that the number of semidaily type tides is slightly greater at Albany than elsewhere, and that at this port equatorial tides are of greater range at the equinoxes than at the solstices. The range of both daily and semidaily type tides is least at Fremantle and increases north and south of this port.

(v) Changes in sea level caused by meteorological and hydrological forces are of the same order of magnitude as those caused by astronomical forces. At Fremantle daily sea level may lie anywhere between 1 ft and 5 ft above datum. Sea level is always higher in winter than in summer; the difference between the highest and lowest monthly means in any one year at Fremantle is about 1 ft. There is considerable variation from year to year.

Sea level varies inversely with the barometric pressure (though the relation is not a simple one) and directly with the temperature of the water. Offshore winds lower and onshore winds raise the sea level.

(vi) Low water of daily type tides is in the early morning in summer, and in the late afternoon in winter; the time only varies by about 2 hours in any half lunar cycle, but gets earlier through the year. The change from morning to evening tides takes place in April-May and from evening to morning in September-November, and in these months the time of L.W. moves through about 8 hours during each half cycle. The time of H.W. is much less constant and ranges from about 6 hours after L.W. to about 6 hours before L.W.

Tides are about 2 hours earlier at Geraldton than at Fremantle and up to about 2 hours later at Albany. Offshore winds may delay and onshore winds advance the time of H.W. as much as two hours; similarly onshore winds delay and offshore winds advance the time of L.W.

(vii) Along the north-west coast from Shark Bay to Wyndham the tides have a very different character. They are semidaily, and of the synodic or phase type characteristic of north Atlantic coasts; spring and neap tides alternate over the 29½ day synodic cycle.

From Roebourne northwards the tidal range is great (over 18 ft at springs), but from Onslow (8½ ft) southwards it decreases progressively and at Carnarvon the spring range is no greater than the range of tropic tides at Geraldton.

Proceeding southwards also, the daily component of the tides increases; at Carnarvon successive tides may be of very unequal height and occasional tides of daily type occur at maximum lunar declination near the solstices.

Acknowledgments

We wish to express our grateful thanks to the following gentlemen who have been of great assistance to us in the examination of the data on which this paper is based, and with advice and criticism in its preparation. Dr. A. T. Doodson, Director of the Liverpool Observatory and Tidal Institute; Dr. J. Gentilli, Senior Lecturer in Geography, University of W.A.; Mr. H. S. Spigl, Government Astronomer, W.A.; and Captain G. D. Tancred, R.A.N., Senior Officer, Hydrographic Service. The responsibility for statements in the paper is, of course, ours alone. Many officers of the Fremantle Harbour Trust, Public Works Department, and Perth Weather Bureau have given us much valuable help on many occasions and this is greatly appreciated. The planimeter measurements of monthly sea level were kindly supplied by the Public Works Department.

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9.—A Preliminary Note on the Duketon Meteorite

By Michael J. Frost*

Manuscript received—16th August, 1957.

The meteorite, which will be called the Duketon meteorite, was found by H. W. Hill in October, 1948. It was resting on the surface of the ground about 10 miles north of Duketon, Western Australia. This is about 80 miles north of Laverton near Mt. Joanna in the Nuleri Land District and is approximately lat. 27° 30′ W., long. 122° 22′ E. No other fragments were found nearby and no history of this fall exists. Although samples of the meteorite were apparently forwarded to the Western Australian Government Chemical Laboratories soon after its original discovery no description has previously been published.

The meteorite is a typical siderite, somewhat flattened in shape (Plate 1, 1 and 2). Most of the meteorite is marked by the usual thumbmarks but the flattened sole is characterised by large flatly concave surfaces. Only one burnt-out troilite rod about 2 cm in length is present on the surface.

The weight of the meteorite, as received, was 260.7 lb, but small fragments, weighing possibly 2.0 lb, had already been removed. The density of a large piece, including the oxidised crust, was determined as 7.64 grams/c.c. Etching of a polished surface indicates that the siderite is a typical medium octahedrite with kamacite plates from 1-1.5 mm in width. A few wider irregular bars of kamacite and a number of irregular veinlets, presumably of taenite, are present (Plate 1, 3). Since the Widmanstatten figures run to the edge of the meteorite considerable weathering must have occurred although no rusting can be seen except on the surface.

A small meteorite, the "Nuleri" meteorite, has also been recorded from the Nuleri Land District and as this is also a medium octahedrite the possibility that both belong to the same fall cannot be overlooked. However, in the absence of detailed work and the exact location of the Nuleri meteorite, it is probably safer to consider them as of separate falls.

The main mass of the meteorite is in the museum of the Geology Department of the University of Western Australia (Specimen No. 38228).

My thanks are due to P. A. Hill for donating the meteorite and supplying information about its occurrence. The photographs of the whole meteorite were taken by the late H. Tarlton Phillipps, and the photograph of the etched surface by Mr. F. Billing.

* Department of Geology, University of Western Australia.

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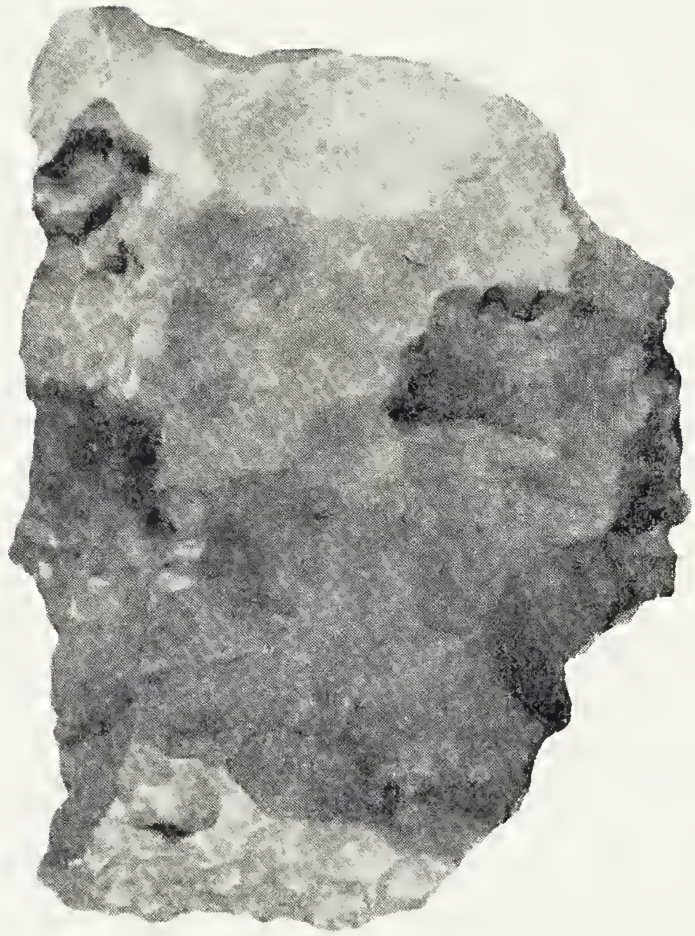

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PLATE 1.

1.—Obverse of Duketon meteorite. Arrow points to burnt-out troilite rod. ($\frac{1}{6}$ natural size.).

2.—Reverse of Duketon meteorite. ($\frac{1}{6}$ natural size.).

3.—Etched surface of meteorite. ($\frac{1}{2}$ natural size.).

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